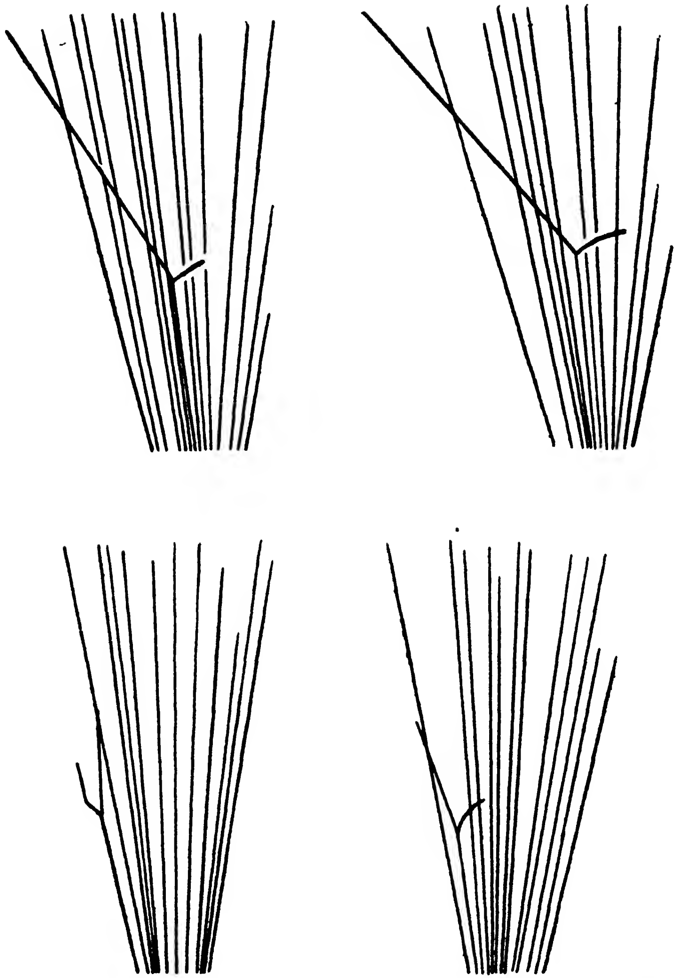

Showing the Collisions of Alpha-Particles with Nitrogen Atoms.

The upper portion of the diagram shows the alpha-particles rebounding from a nitrogen atom. The lower portion shows the expulsion of a proton and the alpha-particle uniting with the atom.—*See page* 63.

THE MID-TWENTIETH CENTURY ATOM

by

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PREFACE

This book is intended primarily for the intelligent and inquiring layman. To some extent it was inspired and has been dominated by the news of the atomic bomb but it is not about the bomb as such. It is about the knowledge, both theoretical and practical, that made the bomb possible; and it should be helpful to those who like to know the whys and wherefores of things as well as the superficialities.

A word is necessary about the title; our knowledge of the atom and its structure has grown rapidly and it has been growing for a century and a half, but it has increased more and to more practical effect in the last decade than in the previous century. How much more and at what speed this knowledge will continue to grow I cannot say, but I have tried to set down within the limits of a little over a hundred pages the salient points in our knowledge, in this Year of Grace 1946, of that mighty ultra-microscopic thing, the atom. I trust that to describe the atom as we know it in 1946 as "The Mid-Twentieth Century Atom" will not be regarded as, nor prove to be, a misnomer. One thing is certain: that the conception of the atom in the middle of the twentieth century is very different from what it was in the beginning and he would be a bold man who asserted that it may not be different again at the end of the century, though this may not concern many of us very much.

It is presumed that most readers have little or no knowledge of either chemistry or physics, and on this assumption some space has been devoted to elementary explanations which may seem tedious to those who have a nodding acquaintance with the subjects. If a few readers feel impatient with detailed expositions of simple matters, they must show forbearance for the sake of the great majority to whom the subject is new and who require plain explanations. Though it has been necessary to introduce a few elementary mathematical formulae in some places, these can be omitted by those whose mathematical knowledge is limited. They are not essential for a *general* understanding of the matters discussed. In most cases the mathematics have

been relegated to the Appendices, where more detailed descriptions are given regarding the methods employed for weighing the electron and other particles, determining their dimensions and velocities, etc.

One apparent defect of this book will almost certainly occur to some—the absence of any exposition of wave-mechanics. This subject has been deliberately omitted because it is certain that the class of readers for whom the book is intended would not understand the mathematics of Schrödinger's wave-mechanics, and even an elementary exposition of this subject requires a considerable amount of mathematics. Throughout the text the Bohr conception of the atom has been adhered to, and as this conception is very easily visualized it is much better that readers should become familiar with it. Those who are anxious to pursue the study of the subject in more advanced books will find on p. 99 a list of standard works from which they can make their choice. It is hoped that this very elementary treatment of the subject will arouse greater interest in a matter which is full of possibilities for future generations and which may revolutionize our whole industrial life.

M. DAVIDSON.

April, 1946.

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Chapter I

THE ATOM IN ANCIENT AND MODERN TIMES

THE word "atom" is derived from the Greek *atomos,* which means a body that cannot be cut in two. The atomic theory of the constitution of matter asserts that it is made up of atoms, and the chemist defines an atom as the smallest particle of matter which can take part in a chemical change—a definition which conveys little meaning to the non-chemist but which will be better understood later when certain points have been made clearer in the chapter. Many people believe that the atomic theory is comparatively new, but this is a mistake. Atomism played a part in Hindu logic, and many centuries before the Christian era Greek philosophers discussed the question of the constitution of matter, some of them advocating the atomic view as the most probable explanation. Although Democritus is usually credited with the honour of being the first Greek philosopher to propound the atomic theory, the real founder of the theory was Leucippus, who lived about the middle or latter half of the 5th century B.C.

GREEK CONCEPTIONS OF THE ATOM

Leucippus believed that the ultimate constituents of all things were empty space and atoms. Empty space was infinite in magnitude and atoms were infinite in number and indivisible and were always in motion, in consequence of which everything happened of necessity. He taught that an infinite number of worlds was produced by variously shaped atoms of different weights falling in empty space and producing eddying motions by their impacts, and not only were worlds being continually produced in this way, but also others were always being destroyed.

Democritus, who was a contemporary of Socrates, but the exact date of whose birth is uncertain, developed the atomic philosophy of Leucippus and held that atoms were the ultimate material of all things, including even spirit, and existed from all eternity. They varied in shape, although they were invisible, and were heavy, extended and impenetrable. Like Leucippus, he taught that the world was produced by the motion of the atoms, and some believe that he advocated a deterministic

scheme in the universe in consequence of which similar atoms come together. His views on the relation between soul and fire are interesting; he taught that these were of one nature and that the atoms composing them were small and smooth. Through inhaling and exhaling these atoms life was maintained, and hence when the body perished the soul perished with it.

Other Greek philosophers took up the study of the subject, but it is unnecessary to deal at length with their work. Reference may be made, however, to Epicurus (342–270 B.C.), who also taught that atoms in their perpetual motions were always giving rise to new worlds and these in turn were always tending towards dissolution and towards a fresh series of creations. Epicurus did not accept the doctrine of inevitable fate, although he did not believe in divine intervention in the universe. It is remarkable that he rejected fatalism while accepting the atomic view of his predecessors, but he was able to explain why fatalism, which he believed to be as deadly to man's true welfare as current superstition, was not a necessary consequence of his atomic theory. In the movements of the atoms he introduced a sudden change in direction which rendered their aggregation easier, and thus the law of destiny was broken.

The views of the Greek philosophers were not so crude as they may seem on a superficial examination, and some of their doctrines show a remarkable similarity to the theories of a number of modern physicists and astronomers. We must deplore the fact that the atomic theory of the ancients did not receive general acceptance; this was due to the influence of Aristotle, whose philosophy was largely responsible for influencing European thought for more than a thousand years, and whose dominance delayed the progress of science in many ways. Not until about the beginning of the 19th century was the atomic theory placed on a sound basis supported by the powerful evidence of experimental fact.

The Constitution of Matter

The modern chemist and physicist regard matter as being composed of aggregations of very small particles to which the name *molecules* (little masses) is given. All molecules of any one chemical compound are alike but they are different for different substances. Thus, the molecule of water is quite different from the molecule of marsh gas, and this again differs from the molecule

of laughing gas, and so on. In each of the three states of matter—solid, liquid, and gaseous—the molecules are in a state of rapid motion, and in the gaseous state, where they have more freedom of movement, the molecules are separated by greater distances than they are in the liquid or solid state. If we divided a substance—say water—into minute quantities and continued subdividing each minute quantity further and so on, a time would come when we could not continue with the subdivision and retain the properties of the water. Aristotle did not believe this. Rejecting the atomic theory advocated by certain Greek philosophers, he believed that the sub-divisions could be continued indefinitely, but we know now that he was wrong. If it were possible to proceed with the divisions a time would come when we should find ourselves with a molecule of water which could not be subdivided without destroying the characteristics of water. Further divisions of the molecule would produce the *atoms* which compose a molecule.

It is very important to distinguish between a chemical compound and a mechanical mixture. If we bring together the molecules of different kinds of matter it is possible for them to mingle without losing their identity. Thus, if we mix saltpetre, sulphur and charcoal in the proportions by weight of 75, 10 and 15 respectively, we shall get gunpowder, which, incidentally, will not prove as serviceable as the gunpowder which we purchase. If we had the time and patience we could separate the small particles of each ingredient from the mixture, and each particle would retain its original properties. The atoms composing each individual molecule remain associated just as they were before we mixed the ingredients to form gunpowder. In cases like these we speak of a *mechanical mixture*, of which there are numerous examples that will occur to the reader.

Molecules and Atoms

If we take some sodium nitrate, known as Chili saltpetre, and mix it with a solution of potassium chloride and then heat the mixture, we shall obtain a precipitate which is sodium chloride, while the solution contains potassium nitrate or saltpetre, which can be crystallized out of the solution. In this case an atom of chlorine has united with an atom of sodium to form sodium chloride, while atoms of nitrogen and oxygen have united with an atom of potassium to form potassium nitrate.

A redistribution of the atoms has taken place to form different molecules, and we could not produce from the precipitate and the solution containing the potassium nitrate the original compounds that were mixed together. In cases like this we describe the result of mixing the different substances as a *chemical compound*, and in the formation of the new molecules, *chemical action* is said to have taken place. One of the simplest examples is the combination of oxygen and hydrogen to form water.

We have not yet defined the term *molecule*; having given a description of certain changes that occur when different substances are mixed together, this will assist in understanding the definitions which follow:

A molecule is the smallest particle of matter in which the original properties of the matter are retained.

The definition of an atom given on p. 9 will now be clearer.

An atom is the smallest particle of matter which can take part in a chemical change.

Everything—whether it be in the solid, liquid or gaseous state—is composed of molecules each of which has the same mass for the same substance. Thus, if we could isolate a molecule of water we should find that its mass was just the same as any other molecule of water that could be isolated. On the other hand, the molecule of water differs in mass from the molecule of iron, and this again from the molecule of oxygen, and so on. At present we are not concerned with the relative sizes of the molecules, nor indeed with their relative masses; we are primarily interested in the masses of the atoms which go to build up the molecules.

Each molecule is composed of atoms, the number of which may vary according to the nature of the molecule. The molecule of hydrogen has two atoms, while that of phosphorus has four. The molecule of water is composed of two atoms of hydrogen—the lightest of all gases—and one atom of oxygen. This is expressed by the chemist in the simple form H_2O, the letters H and O denoting an atom of hydrogen and oxygen respectively, and the figure 2 denoting that 2 atoms of hydrogen are in the molecule. The figure 1 is not used for a single atom, being understood. The molecule of glucose or grape sugar consists of 6 atoms of carbon, 12 of hydrogen, and 6 of oxygen, and is expressed in the form $C_6H_{12}O_6$. The molecule of ordinary table salt, or sodium chloride, to give it its chemical name, consists of 1 atom of chlorine, denoted by Cl, and 1 atom of sodium, denoted by Na (from the Latin *natrium*), the figure 1 not

being used, and hence sodium chloride is expressed in the form NaCl.

The reader should bear in mind that the atom is the unit in building up the molecule, and that, while there may be one, two, three or more atoms in a molecule, there can never be a fraction of an atom. It is like building a wall with bricks, all of which are of the same dimensions. The builder is told that on no account can he break a brick to make an adjustment in the length or height of the wall. He must use bricks that are absolutely intact and, if adjustments are necessary, he must effect them by spacing the bricks properly. We must not press this comparision too far, because, while the atoms, like the bricks, cannot be broken into smaller pieces in the particular construction for which they are intended, unlike the bricks, which are all the same size and weight, the atoms are not all the same size, nor do they all weigh the same. We shall deal with this last point at this stage, i.e. the relative weights, or, to be more correct, the relative masses, of the atoms, but the first expression will be adhered to as the chemist always speaks of "atomic weights", not of "atomic masses".

Relative Weights and Absolute Weights

In several portions of this book we shall refer to *relative* weights, and it is important that the reader should understand clearly the difference between weights expressed in this way and the *absolute* weights of substances. A simple if somewhat crude illustration will show the difference.

We are accustomed to think of weights in terms of ounces, pounds, stones, etc., and if we were asked to estimate the weight of some object by holding it in our hands, most of us could judge this with a fair degree of accuracy. If we are purchasing a commodity it is very important that we should know its weight in so many pounds, stones, etc., as the case may be, and in such circumstances we accept some standard weight as our unit of comparison, this standard weight being common to our country and very clearly defined. In ordinary language, though strictly speaking not quite scientific language, this weight is our *absolute* standard.

Now suppose people are engaged in a competition for estimating weights, and a number of articles that can be picked up are placed in a row and labelled A, B, C, etc. Imagine that

the competition takes place in an Oriental bazaar in which the weights are reckoned in Chinese taels, and some Western visitors, who are ignorant of the Chinese weights and measures system, are invited to compete. Most of them would find great difficulty in estimating weights in terms of the taels unless they were told that a tael was about 1⅓ ounces; but suppose the method of competition were varied slightly, the scheme being as follows:

The Western visitors are informed that the commodity marked A weighs less than any of the others marked B, C, etc., and that all that is required of them is to estimate how many times the weights of B, C, etc., exceed the weight of A. They are not asked to give the numbers of taels in any of the commodities but merely to express the weights of these in terms of the weight of A, whatever that might be. The weight of A is taken as the *unit* in which other weights are expressed. Obviously the Western visitors are not handicapped in the competition because we may assume that they are just as capable as are the Chinese of estimating the weights when they have got one as a standard.

In these circumstances the weights of the objects are known as *relative* weights; that is, their weights are all relative to the weight of A, and it makes no difference that the weight of this in taels is unknown. The terms of the competition render this unnecessary, and everyone—Chinese as well as Western visitors—enters the competition on equal footing.

Relative Weights of Atoms

Everyone is aware of the fact that various substances, taking the same volume in every case, have very different weights. Thus, if we take a small piece of carbon and the same volume of lead, we know that the lead weighs considerably more than the carbon. The same thing applies to the atoms of the various elements. By *element* we mean a substance which cannot be separated into other substances. Thus, lead, hydrogen, carbon, etc., are elements, because we cannot normally separate them into other substances.* A compound is a substance containing two or more elements. Thus, glucose is a compound because it

* The word "normally" is used because, as will appear later, it is possible to transmute certain element into others by methods unknown to the older chemists.

contains more than one element—namely carbon, hydrogen and oxygen. There are 92 elements, and the atoms which compose each of these have different weights, that of the hydrogen atom being the smallest of all, and that of uranium being the largest, weighing 238 times as much as the hydrogen atom.* Again, as with the molecules, each atom of the same element has the same weight, with certain apparent exceptions which will be noticed later, so if we find an atom of hydrogen in any part of the world we know that its weight will be the same as that of the hydrogen atom with which we are familiar when we split up water, by means of the electric current, into hydrogen and oxygen.† We are not concerned at present with the method for weighing atoms and in the meantime we shall merely speak of the *relative* weights of the atoms. Thus, if we denote the weight of the hydrogen atom by 1, that of the oxygen atom will be 16, of chlorine 35·5, of gold 196, and so on.

It has been assumed that molecules are built up from intact atoms, but have we any proof that this is so? No proof has been suggested so far and we shall now proceed to examine the evidence on which John Dalton, a famous chemist, formulated his theory of the atoms. While the evidence that follows cannot be considered absolutely conclusive, it will be obvious that the probability of such remarkable coincidences taking place, if the atom is not the unit in the building of the molecule, is extremely remote. So remote indeed is the probability of mere chance being the deciding factor that we can regard Dalton's theory as firmly established as most of the scientific theories that are accepted today without question.

* This statement requires some modification in view of recent developments (*see* p. 104).

† The heavy isotope of hydrogen is excluded from consideration at present (*see* p. 68).

Chapter II

DALTON'S ATOMIC THEORY

In 1804 Dalton advocated his theory of the atomic composition of bodies, though his ideas had been foreshadowed about thirteen years earlier by W. Higgins, of Pembroke College, Oxford. The atomic theory first suggested itself to Dalton while he was investigating marsh gas and ethylene, or olefiant gas, both of which are composed of carbon and hydrogen in different proportions. Dalton saw that if the weight of carbon in each of these gases were considered to be the same, then marsh gas contained twice the weight of hydrogen present in olefiant gas. Another observation which he made and which seemed very significant to him was that the quantity of oxygen in carbon dioxide, the gas which we exhale, was twice as much as that in carbon monoxide, the dangerous gas which results from incomplete combustion due to a deficiency of oxygen. From these and other facts he conceived that an explanation could be offered if the ultimate particles of matter were assumed incapable of further division—that is, if the ultimate particles were *atoms* possessing definite weights, the ratios of which could be denoted by numbers. Embracing the ancient doctrine of atoms, Dalton extended it into the scientific theory known as Dalton's atomic theory.

Dalton's atomic theory states that matter consists of aggregations of minute particles or atoms which are indivisible. As will be seen later, comparatively recent research has shown that this last conception of the atom is not quite correct, because the atom has been found to consist of minute elementary particles. Dalton believed that chemical combination between two elements took place owing to the union of their atoms through "chemical affinity". He further assumed that the atoms of various elements had different weights and that a definite relation existed between these weights which could be discovered by experiment. As an example of this, take the case of a few elements which combine and whose masses in the combination have been measured.

Verification of Dalton's Theory

The most obvious way of stating the composition of a compound is as parts of 100. Thus, if a chemist analyses 20 grams of lime and finds that they contain 14·286 grams of calcium and 5·714 grams of oxygen, the percentage composition is found to be as follows:

$$\begin{array}{lr} \text{Calcium} & 14{\cdot}286 \times 100/20 = 71{\cdot}43 \\ \text{Oxygen} & 5{\cdot}714 \times 100/20 = \underline{28{\cdot}57} \\ & 100{\cdot}00 \end{array}$$

It is convenient at present to take hydrogen as the unit in giving the weights of other elements, because hydrogen is the lightest known element. The percentage composition of a few compounds which have hydrogen as one of their constituents is given in Table I, the last column showing the figures if hydrogen is taken as the unit.

Table I

Name of Compound	*Chemical*	*Composition of 100 parts by Weight*	*Composition if Hydrogen = 1, or if Hydrogen is the unit of Weight*
Water	H_2O	Hydrogen 11·1 Oxygen 88·8	1 8
Hydrochloric acid	HCl	Hydrogen 2·74 Chlorine 97·26	1 35·5
Ammonia	NH_3	Hydrogen 17·65 Nitrogen 82·35	1 4·6
Methane	CH_4	Hydrogen 25 Carbon 75	1 3
Ethylene	C_2H_4	Hydrogen 14·29 Carbon 85·21	1 6
Acetylene	C_2H_2	Hydrogen 7·69 Carbon 92·31	1 12

It will be seen that simple numbers are often obtained when hydrogen is taken as the unit, the numerical relations being concealed when percentages are used. Thus, in the three carbon compounds in the table we notice that 1 of hydrogen unites with 3, 6, and 12 of carbon. The smallest proportion ever found in any carbon compounds is 3.

The table could be extended to include a great many other compounds which contain hydrogen, but the few cases given will be sufficient as examples of the principle we are trying to emphasize. Of course all compounds do not contain hydrogen, and it is necessary to deal with those which have no hydrogen in their composition, as is done in the next table.

TABLE II

Name of Compound	*Chemical Formula*	*Composition of* 100 *parts by Weight*	*Composition if Chlorine* = 35.5 *by Weight*
Chlorine monoxide	Cl_2O	Chlorine 81·61 Oxygen 18·39	Chlorine 35·5 Oxygen 8·0
Chlorine peroxide	ClO_2	Chlorine 52·59 Oxygen 47·41	Chlorine 35·5 Oxygen 32·0
Chlorine heptoxide	Cl_2O_7	Chlorine 38·80 Oxygen 61·20	Chlorine 35·5 Oxygen 56·0
Carbon tetrachloride	CCl_4	Chlorine 92·10 Carbon 7·90	Chlorine 35·5 Carbon 3·0
Cuprous chloride	Cu_2Cl_2	Chlorine 35·85 Copper 64·14	Chlorine 35·5 Copper 63·5
Cupric chloride ..	$CuCl_2$	Chlorine 52·79 Copper 47·21	Chlorine 35·5 Copper 31·75

One other table is compiled in which the weight of oxygen is taken as 16.

TABLE III

Name of Compound	*Chemical Formula*	*Composition of 100 parts by Weight*	*Composition if Oxygen = 16 by Weight*
Nitric oxide ..	NO	Oxygen 53·3 Nitrogen 46·7	Oxygen 16 Nitrogen 14
Nitrous oxide ..	N_2O	Oxygen 36·4 Nitrogen 63·6	Oxygen 16 Nitrogen 28
Nitrogen trioxide	N_2O_3	Oxygen 63·2 Nitrogen 36·8	Oxygen 16 Nitrogen 9·3
Carbon monoxide	CO	Oxygen 57·1 Carbon 42·9	Oxygen 16 Carbon 12
Carbon dioxide ..	CO_2	Oxygen 72·7 Carbon 27·3	Oxygen 16 Carbon 6
Cuprous oxide ..	Cu_2O	Oxygen 20·1 Copper 79·9	Oxygen 16 Copper 63·5

A careful study of these tables, which are typical of many others that could be compiled, shows that in some cases the proportions in which two elements combine with one of hydrogen are also the proportions in which they unite with one another. Thus, 8 of oxygen combine with 1 of hydrogen to form water, and 35·5 of chlorine combine with 1 of hydrogen to form hydrochloric acid, and, as the second table shows, 8 of oxygen combine with 35·5 of chlorine to form chlorine monoxide.

These tables exemplify three of the four laws which are the foundations for the structure of modern chemistry, and those who have an elementary knowledge of chemistry will recognize the illustration of these laws without further explanation. These laws are known as the law of constant proportion, the law of multiple proportions, and the law of reciprocal proportions or of equivalent proportions. It is unnecessary to explain these in detail because such an explanation is not relevant to the main object of this book.

The atomic weights of a few well-known elements are given below, that is, the relative weights of the atoms of these elements, the weight of an atom of hydrogen being taken for the present as the unit. A full list of atomic weights is given on p. 44, and the figures for these differ very slightly from those just given, but the reader need not concern himself at present with this apparent discrepancy. Notice that there is no object in defining the weight of an atom of hydrogen, just as there was no object in defining the weight of the tael in the Chinese bazaar. If we were given the weight of the hydrogen atom we could easily calculate the weights of the other atoms, knowing their atomic weights, but at this stage the information would not be of much assistance to us.

TABLE IV

ATOMIC WEIGHTS OF A FEW ELEMENTS

Element	*Symbol*	*Atomic Weight*
Hydrogen ..	H	1
Carbon ..	C	12
Nitrogen ..	N	14
Oxygen ..	O	16
Chlorine ..	Cl	35·5
Copper ..	Cu	63·5

Different methods for the accurate determination of atomic weights are employed, but it is unnecessary to deal with these in this book.

Suppose we take one of the compounds given in Table III, say carbon dioxide. Can we verify Dalton's theory of the atomic constitution from our knowledge of the composition of this and other compounds? To simplify the problem as much as possible we shall make the assumption, which will later be shown to be valid, that the carbon dioxide molecule is composed of 1 atom of carbon and 2 atoms of oxygen, and therefore, in accordance with what has been previously said (see p. 12), the chemical formula for carbon dioxide is CO_2.

Accepting the atomic weights given above, we can say that

the weight of a molecule of carbon dioxide, taking the weight of the hydrogen atom as the unit, is

$$1 \times 12 + 2 \times 16 = 12 + 32 = 44.$$

The percentage composition of carbon dioxide is easily found from these figures. The percentage of carbon is $12 \times 100/44 = 27{\cdot}3$, and that of oxygen is $32 \times 100/44 = 72{\cdot}7$. These are the actual figures obtained by the analysis of carbon dioxide, and so far Dalton's theory is supported by experimental evidence.

Do the percentage compositions of the other compounds also verify the theory? Let us take acetylene, and assume that its chemical formula is C_2H_2. In this case the molecular weight of the compound is $2 \times 12 + 2 \times 1 = 24 + 2 = 26$. Hence the percentage weight of hydrogen is $2 \times 100/26 = 7{\cdot}69$, and of carbon is $24 \times 100/26 = 92{\cdot}31$, and these are the figures obtained from an analysis of the compound, as shown in Table I. Various other compounds can be tested in the same way, as the reader can prove by making use of the chemical formulae given in column 2 of the tables.

The point that has been emphasized in the last few pages is that atomic weights are represented by simple numbers and that the use of these numbers provides us with the observed proportions by weight of the various elements composing the compound. Of course the chemist first of all carried out experiments to determine the percentage composition of various compounds and from this deduced the atomic weights, but the reversal of the process will, it is hoped, make the explanation simpler.

It may interest readers to attempt to fit in the observed percentage composition of the compounds with assumed atomic weights which are not whole numbers. Apparent exceptions to the whole number rule occur in the case of copper and chlorine, but the exceptions are only apparent, as will be explained later. These elements which appear to violate the rule have been deliberately introduced at this stage so that the reader will understand the reason for these apparently anomalous cases (see p. 23).

We have dealt only in a cursory manner with atomic weights and for further information readers can consult books on chemistry. Various other arguments in favour of the atomic theory of matter have been advanced, but as this is not a book on chemistry it is unnecessary to consider them. It may be accepted as an established fact that the atom is the unit in chemical reactions, no fraction of an atom taking part in a chemical

change. From the description of certain chemical reactions given in the preceding pages and also of the meaning of relative weights, the reader will have no difficulty in understanding the following definition of atomic weight:

The atomic weight of an element is the number which represents how many times heavier the smallest mass of that element capable of taking part in a chemical change is, than the smallest weight of hydrogen which can so function.

This definition is sufficient at present, but, as will appear later, chemists have found it more convenient to take one-sixteenth of the weight of the atom of oxygen as the unit.

Valency

When chlorine unites with hydrogen the combination takes place between 1 atom of chlorine, relative weight 35·5, and 1 atom of hydrogen, provisional weight 1. When, however, oxygen combines with hydrogen, 1 atom of oxygen combines with 2 atoms of hydrogen to form water, denoted by H_2O. Ammonia, NH_3, consists of 1 atom of nitrogen combined with 3 atoms of hydrogen. When carbon unites with hydrogen to form methane, CH_4, 1 atom of carbon unites with 4 atoms of hydrogen.

One atom of chlorine never combines with more than 1 atom of hydrogen, and this is expressed by saying that the affinity of chlorine for hydrogen is satisfied or saturated by union with 1 atom. One atom of oxygen requires 2 atoms of hydrogen for saturation. Nitrogen requires 3 atoms of hydrogen, and carbon requires 4, to satisfy their affinities for hydrogen. Many other instances occur in which 1 atom of an element unites with 1 atom of hydrogen, as in the elements fluorine, bromine and iodine, which resemble chlorine in this respect.

The combining capacity of an element is known as its *valency*, and elements like chlorine, fluorine, etc., one of whose atoms is capable of uniting with only 1 atom of hydrogen, are called *monovalent* elements, or sometimes *monad* elements. Where 1 atom of elements combines with 2, 3, or 4 hydrogen atoms the elements are known as *divalent* or *dyad*, *trivalent* or *triad*, *tetravalent* or *tetrad* elements. In cases where an element does not enter into chemical combination with hydrogen but enters into combination with some other monovalent element, its valency is measured by the number of atoms of this mono-

valent element capable of satisfying their combining capacity. Thus, calcium combines with chlorine to form calcium chloride, $CaCl_2$, 2 atoms of chlorine combining with 1 atom of calcium, and since chlorine is monovalent, calcium is divalent.

Elements do not always show the same valency when they are measured by their combining capacity with hydrogen and chlorine, but in such cases the highest number of monovalent atoms with which an atom of the element is capable of combining is usually accepted as the valency of that element. Thus, while 1 atom of phosphorus combines with 3 atoms of hydrogen to form hydrogen phosphide, PH_3, it also combines with 5 atoms of chlorine to form phosphorus pentachloride, PCl_5, and hence phosphorus is regarded as a pentavalent element.

The subject of valency has been introduced primarily to assist in the explanation of certain phenomena connected with electrolysis, about which something is said in *Chapter III*.

It is slightly disconcerting to find that the atomic weights of some elements are not exact whole numbers, as, for instance, in the case of chlorine and copper, and there are many other similar elements whose atomic weights are whole numbers and a fraction. It will be better to clear up this difficulty at this stage, to make it easier for the reader to understand what follows in *Chapter III*.

Isotopes

It has been found that a number of elements, such as chlorine, oxygen, nitrogen, and many others, consist each of atoms of different weights. Take for instance the case of chlorine. It is now known to be a mixture of two different kinds of atoms, 75 per cent of which have weight 35, that of hydrogen being the unit, and 25 per cent of which have weight 37. Now suppose we mix two gases in the above proportions, what result would we expect? The solution is a simple arithmetical problem and is shown below:

$$(75 \times 35 + 25 \times 37)/100 = 35{\cdot}5.$$

We should expect ordinary chlorine, therefore, to have an average atomic weight of 35·5, and its actual atomic weight is given as 35·46, which is a good enough agreement.

Ordinary atmospheric nitrogen consists of two different

kinds of nitrogen. One has an atomic weight of 14, and this forms 99·7 per cent of atmospheric nitrogen; the other has an atomic weight of 15 and forms only 0·3 per cent of atmospheric nitrogen. Hence the average atomic weight of the mixture is

$$(99{\cdot}7 \times 14 + 0{\cdot}3 \times 15)/100 = 14{\cdot}003.$$

This differs very little from the usually accepted value—14—but if there were 50 per cent of each kind of nitrogen present the average atomic weight of the mixture would be 14·5.

The name *isotope* is given to those atoms that have the same chemical properties but differ in their mass. The heavier isotope of chlorine has precisely the same chemical properties as the lighter isotope, and the same applies to other isotopes. The word *isotope* means occupying the same place, and the reason for this name will be seen later when we come to deal with the structure of the atom.

As this is not a treatise on chemistry, only the main points connected with the atom have been referred to, and it is hoped that these will be sufficient to enable the reader who has no knowledge of chemistry to understand the remaining chapters, which deal amost entirely with the atom. A knowledge of chemistry, while advantageous for following some portions of the book, is by no means necessary, and those who have never read even an elementary book on chemistry need not be deterred from reading the remaining chapters.

Chapter III

THE MODERN CONCEPTION OF THE ATOM

In the previous chapter a brief reference has been made to molecules, which consist of atoms, either of the same kind—in which case they are termed elementary molecules, such as hydrogen, the molecule of which has two atoms—or of dissimilar atoms, in which case they are called compound molecules, such as water, but nothing was said about the sizes and absolute masses of molecules and atoms. The relative masses only of the atoms were considered. Our concern is primarily with the atom, and we shall confine our attention mainly to it in the remainder of the chapter, dealing first of all with its constitution

and then with certain quantitative results regarding the hydrogen atom—the simplest of all atoms.

It will be necessary to use the metric system in which physicists always carry out their calculations, and a comparison between the units in this system and those in the English system (in which engineers usually work) is essential for the reader who thinks only in the English system. A more comprehensive table is given on p. 124.

A centimetre, the unit generally adopted for measuring engths, is 0·4 inch, and a gram, in which masses are reckoned, is 0·0022 pounds or about one-twenty-eighth of an ounce, or 15·4 grains. As very small quantities will be dealt with—extremely minute fractions of a centimetre and a gram—the method adopted for denoting these is as follows:

When we speak of an object as possessing a diameter of one-tenth, one-hundredth, one-thousandth, etc., of a centimetre, these lengths are denoted by 10^{-1}, 10^{-2}, 10^{-3} cm., etc., the abbreviation cm. being used. Thus, instead of describing an atom with a diameter of one-one hundred millionth of a centimetre, it is simpler to say that its diameter is 10^{-8} cm., and it will be noticed that the number of cyphers in one hundred million is 8, which is the same figure, with a negative sign prefixed, used as the index of 10. In the same way, if we wish to describe the five-million millionth of a gram we merely say that the mass of the object is 5×10^{-12} gm., the number of cyphers in a million million being 12. This method possesses many advantages, not only in computations but also in descriptions, because in some cases much more than 20 cyphers are required to describe dimensions, and it is confusing to attempt to do so in words instead of by figures as suggested.

The conception of the atom is something like the view we hold of our solar system—a massive central body like the sun, round which revolve a number of less massive bodies—the planets. There is a certain amount of similarity between the relative masses of the planets and the sun and the relative masses of the electrons, and the nucleus of the atom. (A description of the terms "electron" and "nucleus" is given later.) There is also a similarity between the distances of the planets from the sun and the distances of the electrons from the nucleus. The similarity ends with this and we cannot apply the same law—the law of gravitation—which causes the planets to revolve round the sun to the nucleus of an atom and the electrons revolving round it: a different law prevails here.

The Electron

The electron—sometimes called the negative electron or the negatron—is a very minute and also a very light particle which carries one negative electrical charge. It was discovered during the observation of phenomena which occurred when an electrical discharge was passed through a very rarefied gas. A rough sketch of the apparatus employed for observing these phenomena is shown in Fig. 1.

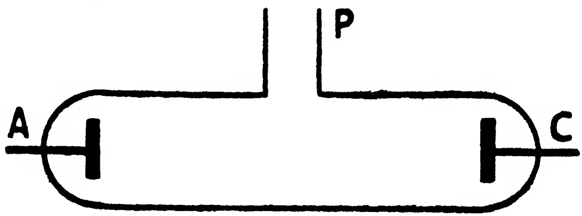

Fig. 1.
Production of the cathode rays in the vacuum tube.

Cathode Rays

A glass tube has two platinum electrodes *A* and *C*, one sealed in at each end, and each of these is connected to a source of high voltage—a few thousands up to a few tens of thousands of volts, direct current. Under ordinary circumstances gas is a comparatively poor conductor of electricity, but if the potential is sufficiently high the insulating properties of the gas break down, as in the case of a lightning flash through the atmosphere. If the pressure in the tube is reduced by means of an air pump at *P*, a point is reached at which the conductivity of the gas is sufficient to allow a current to pass, and a luminous column then appears between the electrodes. When the pressure is lowered still more—to about 10^{-6} of an atmosphere—the conductivity of the rarefied gas now diminishes and the walls of the tube emit a greenish or bluish glow. The chief interest lies in the source of this glow, and it is easily located from the fact that if some object is placed between the negative electrode (known as the cathode) and the glass it casts a shadow (Fig. 2). The cathode is the source of some form of emanation which causes the glass

to glow, and the name *cathode rays* was given to this emanation because it originated at the cathode. When they were first discovered their nature was not properly understood and various theories were advanced to explain them. Experiments conducted by physicists, more especially by J. J. Thomson, showed that these rays, irrespective of the nature of the gas in the tube, always manifested certain properties, amongst which the following may be noticed:

They travelled in straight lines away from the cathode—a fact easily deduced from noticing the form of shadow thrown by the solid object. This was geometrically similar to the form of the object.

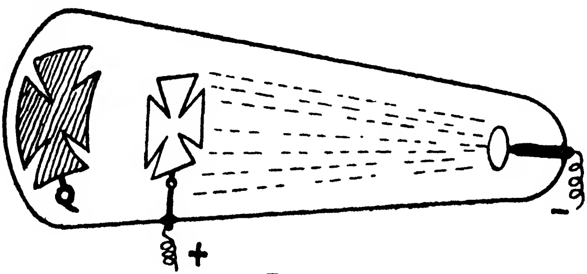

FIG. 2.
The shadow cast by the cathode rays shows that they travel in straight lines from the cathode.

They produced luminescence when they impinged on various types of material, not only on the walls of the tube but also on certain minerals such as willemite—a natural silicate of zinc.

The rays were bent by an electrical or a magnetic field. An ordinary bar magnet brought near them caused the phosphorescence to appear on different parts of the glass tube, and the deflection was in such a direction that a stream of negatively charged particles would be expected in consequence. Proof of the negative charge carried by the rays was afforded by allowing them to impinge on an insulated electrode connected to an electroscope, the movements of whose leaves left no doubt as to the nature of the charge carried by the rays.

They were capable of producing mechanical effects—such as driving a very small windmill whose vanes were placed in their path.

They passed through thin sheets of metal and hence were of a different nature from ordinary light rays.

These properties suggested that the cathode rays were streams of electrons torn from the atoms of the gas in the tube and then repelled by the negative electrode—the cathode—with very high speed. The fact that they possessed the same properties, whatever the gas in the tube, suggested that the atoms of different elements were composed of the same kind of units and hence that the electron is a constituent of all atoms.

Naturally the physicist was anxious to know something more about these mysterious particles—in particular about their masses and speeds and the charge that each one carried. Wiechert and Kaufmann in 1897 had obtained certain results showing the approximate relation between the charge and the mass of an electron, but the main research was carried out by J. J. Thomson, who obtained more accurate results than the physicists just referred to, though his results have been superseded by more recent ones of still greater accuracy. An outline of the method employed to measure the mass and speed of the electron is given in *Appendices I–IV*, but readers who are not conversant with certain elementary principles in electricity and magnetism can omit this portion and accept the results, a summary of which is given below.

The velocities of the cathode particles ranged from about 6,000 to 60,000 miles per second, according to the voltage used in the tube.

The relation between the charge e carried by each particle and its mass m was always the same, whatever the nature or pressure of the gas in the tube, or the metal used as cathode. This relation is expressed by the ratio e/m and it was found to be about $5{\cdot}27 \times 10^{17}$ electrostatic units per gram, usually expressed in the form $5{\cdot}27 \times 10^{17}$ e.s.u./gm. (See *Appendix II* for an explanation.)

In the case of hydrogen ions (*see* Electrolysis in next paragraph) this ratio e/m has been found to be $2{\cdot}87 \times 10^{14}$ e.s.u./gm., which is about 1844 times less than it is for the electron. Obviously, if the mass of the hydrogen ion is 1844 times that of an electron, we have an explanation of this fact, and this ratio has been universally accepted. A hydrogen ion (or atom, as the mass of each is practically the same) has therefore about 1844 times the mass of an electron.

Electrolysis

The name *electrolysis* is applied to the decomposition of a compound·liquid, its two components being separated when an electric current is passed through it, one at the place where the current enters, and the other where it leaves the liquid.

At the beginning of the 19th century it was discovered that when a current of electricity was passed through water to which a little sulphuric acid had been added, bubbles of gas rose from each electrode, and it was found that the gas evolved at the negative electrode was hydrogen and that at the positive electrode was oxygen. This is the simplest form of electrolysis and the phenomenon will now be considered in connection with solutions of various compounds, called electrolytes.

The name *electrolyte* is applied to the dissolved substances themselves, such as copper sulphate, common salt, etc., because when they are dissolved in water they form electrically conducting solutions. During electrolysis one portion of the salt travels to the positive pole or positive electrode—the *anode*—and the other portion travels to the negative electrode—the *cathode*. Thus in the case of common salt, or sodium chloride, chlorine is liberated at the anode and sodium at the cathode. No perceptible chemical action is noticed in the electrolyte during the process of electrolysis, except at the electrodes where the *ions* are liberated. The name *ions* is given to the parts of the electrolyte that move to the electrodes, the *anions* arriving at the anode and the *cathions* at the cathode. Thus in the electrolysis of water the oxygen ions are the anions and the hydrogen ions the cathions, and in the electrolysis of common salt the chlorine ions are the anions and the sodium ions the cathions. The hydrogen atom which has lost its one and only electron, and is then a hydrogen ion, has been given the special name *proton*.

There is a definite relation between the quantity of electricity passed through the electrolytes and the weights of the ions deposited at each electrode. Faraday found a result which can be expressed in modern terms by saying that the weight of different metals deposited by a given current in a given time is proportional to the atomic weight of the element divided by its valency. Faraday's laws were so accurate that they were used to define the international ampere; the accepted definition is: "that current which, flowing uniformly for one second, deposits under specified conditions 0·001118 gm. of silver from a solution

of silver nitrate". The charge carried by a monovalent atom such as silver forms a natural unit of charge, and Faraday's laws are just what we would expect if the atoms of various elements carried the current, each atom bearing a charge proportional to its valency.

The explanation of electrolysis will be made simpler by referring to Fig. 3. The battery passes a current through the electrolyte in which streams of charged ions to the two electrodes

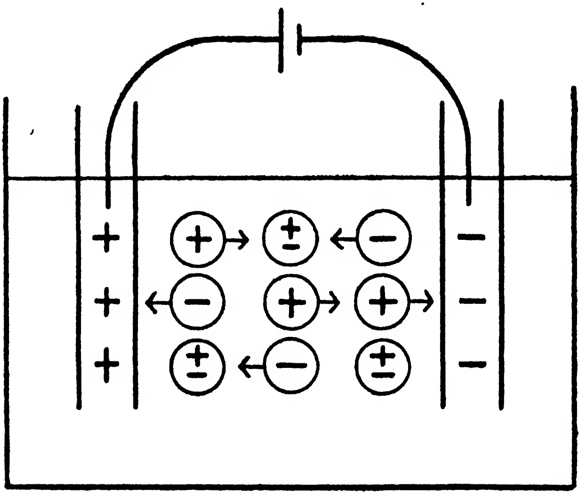

FIG. 3.

Electricity is carried across from one electrode to the other by charged ions which are attracted to the electrodes, and the current is thus conveyed in the electrolyte.

move in opposite directions. The ions are attracted to the electrodes—the sign of the charge on the ion being opposite to that of the electrode towards which it moves. Anions are negatively charged atoms and cathions positively charged atoms, and hence the former move towards the positive electrode—the anode, and the latter move towards the negatively charged electrode—the cathode. Electricity is carried across from one electrode to the other by the charged ions, and the current thus conveyed in the electrolyte completes the current passing through the metallic circuit outside the cell.

These experiments in electrolysis afford very strong pre-

sumption for the existence of atoms of electricity, though they do not amount to absolute proof. The solutions behave as we should expect if the electric charges were divided into units as suggested, but other explanations are possible. Absolute proof could be obtained only if one of Faraday's units could be separated from the atom carrying it, and this was not forthcoming until the cathode rays, already referred to, were investigated. It is interesting to note that in 1874 a paper was read at the British Association in Belfast by G. Johnstone Stoney, but was not published until 1881, in which he gave an account of his calculations of the charge associated with the hydrogen atom in electrolysis. He found that this unit charge was $1 \cdot 592 \times 10^{-19}$ coulomb, a result not far from that found by Millikan in 1912. (See *Appendix IV.*)

Electrolysis has very important applications, not only in enabling the chemist to analyse the nature of various compounds, but also in the commercial world. It is applied in the manufacture of such useful metals as sodium, potassium, aluminium, etc. Sodium and potassium were first isolated by Davy by the electrolysis of the hydroxides of the metals, and the modern process adopts the same principle with various modifications resulting from improved technique.

Beta-Rays

The cathode rays are not the only source of electrons. Since the discovery of radio-active materials in 1896 it has been known that these emit streams of electrons to which the name beta-rays has been given (these rays are generally known as β-rays, β being the Greek letter beta), the main difference between electrons and β-rays being in their origin. The β-rays have generally greater velocities than the electrons, and in some cases these rise as high as 99·8 per cent of that of light. By heating metals or by exposing them to X-rays or ultra-violet light, streams of electrons are given off, and the value of e/m in these cases is the same as in the case of the cathode rays,* within the range of experimental error, thus showing that the particles are identical. More will be said about these rays later; meanwhile we shall turn our attention to another type of rays also found in the discharge tube.

* The masses of the β-rays have been found to vary with their speeds. This is in accordance with Einstein's theory. (See *Appendix V.*)

Positive Rays

The cathode rays consist of electrons broken off from atoms and molecules in the discharge tube and driven off from the cathode by the electrostatic field. This fact immediately suggests that there must be present in the discharge tube positive particles, because it is impossible to conceive of negative charges without the corresponding positive charges if a state of electrical equilibrium previously existed. These positive rays were discovered in 1886 by Goldstein and received their first title "canal rays" from the apparatus which he used at the time of their discovery. The cathode of the discharge tube had some fine holes bored through it and Goldstein observed that through each of these holes there appeared to come a luminous ray in a direction away from the anode or positive electrode. He called these rays "*Kanalstrahlen*", which appears in English as "canal rays", but the usual title is *positive rays*.

The properties of these rays were investigated by methods similar to those used in the investigation of the properties of the cathode rays. They produce phosphorescence when they strike against the sides of the glass tube, but the phosphorescence is of a different character and in general not so bright as that produced by the cathode rays. They gradually remove a thin deposit of metal from the walls of the tube against which they strike. Such thin deposit can be produced by passing an electric discharge through the tube when it contains gas at a low pressure, using for the cathode a piece of the metal which it is required to deposit. The metal cathode "splutters" and the metal is deposited as a thin layer close to the cathode.

For twelve years these rays failed to show any effects from exposing them to a magnetic field. We have seen that a magnet held near a bundle of cathode rays produces quite an appreciable deflection, but no such effect was observed with the positive rays until 1898, when Wien showed, by means of very powerful magnetic fields, that positive rays were deflected by magnetic forces. He proved that the positive rays contained electrified particles, and the direction of deflection showed that they were positively charged. The value of e/m was found to differ according to the gas used in the tube—unlike the cathode rays—and it was shown that these particles were much more massive than those in the cathode rays.

When the value of e/m is determined for positive rays,

hydrogen being the gas employed in the tube, it is found that this ratio is about $2{\cdot}87 \times 10^{14}$ e.s.u./gm.*, which is the same as that for the hydrogen ion in electrolysis. As ions are never found with a greater value than this, it affords good reason for believing that the hydrogen atom consists of a nucleus and only one electron revolving round it, and when that one is removed from it the nucleus is left—the hydrogen ion, to which, as has been previously mentioned, the name proton is given. The charge on the proton is equal in magnitude but opposite in sign to that of the electron; that is, $4{\cdot}80 \times 10^{-10}$ e.s.u. From the data the mass of the proton and therefore of the hydrogen atom has been found to be $1{\cdot}672 \times 10^{-24}$ gm. (See *Appendix IV* for a short proof of this.)

The proton can be represented in the form ${}_1H^1$, H denoting the hydrogen ion, the upper 1 denoting its mass number, or the nearest whole number to its atomic weight, and the lower 1 denoting that it carries one electric charge. Normally the hydrogen atom is neutral, the positive charge of the nucleus being neutralized by the electron which revolves round the nucleus. The removal of this electron leaves the nucleus—the proton—with one positive charge.

If helium instead of hydrogen is used in the discharge tube e/m is equal to $1{\cdot}44 \times 10^{14}$ e.s.u./gm., which is just half that found when hydrogen is used. From this it can be deduced that the mass of the helium atom is four times that of the hydrogen atom (see *Appendix IV*), which is four times that of the hydrogen ion. Hence the helium ion can be represented in the form ${}_2He^4$, which implies that its mass number is 4 and its charge 2. When helium is used in the discharge tube the positive rays are identical with the nuclei of helium atoms.

Conception of the Atom in General

Imagine a very miniature solar system in which the sun is replaced by a nucleus carrying with it one or more charges of positive electricity (one in the case of hydrogen atom, two with the helium atom, and so on for various elements), and in which the planets are replaced by electrons revolving round the nucleus. This gives us a pictorial representation of the structure of the atom, with certain modifications. The planets have

* An explanation of these units and of the results obtained appears in *Appendices I–IV*.

not the same masses—Jupiter, the heaviest of all, being more than 8,000 times the mass of Mercury, the lightest of the planets—whereas all electrons have the same mass. Then the planets revolve round the sun nearly in the same plane, but electrons do not revolve round the nucleus even approximately in the same plane. Like the orbits of the planets which are ellipses*

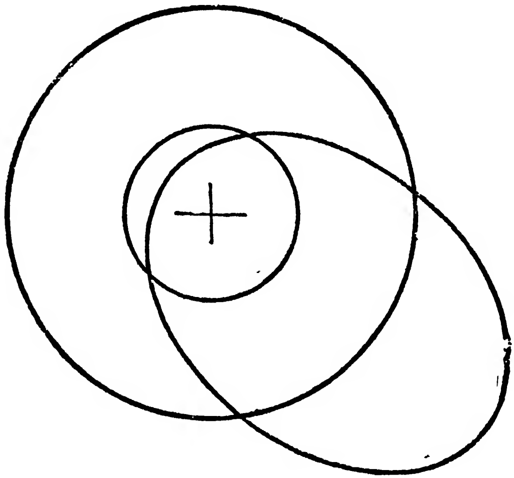

FIG. 4.
The orbits of electrons can be circles or ellipses and these orbits of the electrons of any particular atom need not necessarily lie in the same plane.

(though that of Venus is nearly a circle), the orbits of the electrons can be ellipses or circles, and some of the ellipses are very much more elongated than others. (*See* Fig. 4.)

Conception of the Hydrogen Atom

The simplest of all atoms, as we have seen, is the hydrogen atom, because it consists of the nucleus—the proton—and one electron. Normally the diameter of the hydrogen atom is of the order 10^{-8} cm., but this varies because the electrons of all

* If a circle of wire is taken and it is squashed in on two opposite sides, the figure produced resembles an ellipse. It is oval-shaped, like a Rugby football.

atoms, those at the greatest distance from the nucleus in particular, can alter their distances from the nucleus. (The name "planetary" is sometimes given to the electrons revolving round the nucleus.) Although the dimensions of the atom are known, those of the nucleus and electrons are doubtful, but it is believed that they may be about 10^{-5} the size of the whole atom; that is, their diameters are about 10^{-13} cm. If we wish to compare their volumes it is necessary to raise 10^{-5} to the third power, so that the volume of the nucleus or of an electron is 10^{-15} that of an atom. The above figures show that most of an atom consists of empty space, the nucleus and electrons occupying only a minute fraction of the space occupied by the whole atom reckoned from the nucleus to the most extreme electron revolving round it. The same applies to the solar system, the volume of the sun and planets being extremely small in comparison with the total volume of the sphere which has the sun for its centre and the distance of Pluto—the outer planet—for its radius.

Conception of the Helium Atom

The helium atom in its normal unelectrified state has two electrons and, as these must be neutralized by positive charges, the nucleus has twice as much positive electricity as has the hydrogen nucleus. The next element, lithium, has 3 electrons and 3 charges of positive electricity, and beryllium has 4 electrons and 4 positive charges attached to the nucleus, and so on for other elements. Uranium, the heaviest of all the elements,* has 92 electrons revolving round the nucleus, which has 92 positive charges in its normal state to neutralize the planetary electrons.

It has been seen that helium has two planetary electrons and that its nucleus is four times the mass of the nucleus of hydrogen, or four times the mass of a proton. If we assume that the nuclei of elements other than hydrogen are made up of protons, that of helium containing 4, that of lithium, whose atomic weight is 7, containing 7, that of beryllium, whose atomic weight is 9, containing 9, and so on, a difficulty arises unless we postulate the existence of electrons associated in some way with the nuclei. Thus, in the case of helium, if each of its 4 protons carries a positive charge, then, as there are only two planetary electrons, it is necessary to postulate 2 more nuclear electrons to

* Heavier elements are now produced artificially (*see* p. 104).

produce electrical neutrality. Again, in the case of the lithium atom, which may be assumed to contain 7 protons, if each of these carries a positive charge, then since lithium has only 3 planetary electrons, there must be 4 more nuclear electrons to produce neutrality, and the same applies to other elements.

Difficulties arise in postulating electrons in the nucleus, and these have been overcome by the discovery of the neutron by Chadwick in 1932—a discovery which has assisted considerably in simplifying our conception of the nucleus of the atom.

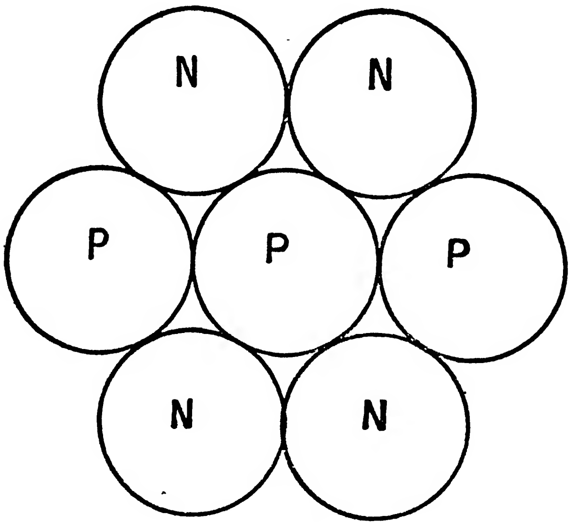

FIG. 5.

The nucleus of an atom is believed to consist of a number of protons and neutrons. Each proton carries one positive charge but the neutron has no charge.

THE NEUTRON

The neutron has almost the same mass* and is probably about the same size as the proton, but, as its name implies, it is electrically neutral, not being associated like the proton with a

* If the mass of a hydrogen atom be represented by 1·008 (see p. 44), the mass of a neutron is 1·009.

positive charge. Let us see how the neutron, which is not postulated merely to simplify certain conceptions about the atom, but which has as real an existence as the proton, explains some of the difficulties just referred to, without invoking the aid of nuclear electrons.

Consider a nucleus of mass 7 units and charge 3 units. Assuming that each proton carries a positive charge, it is possible to build this nucleus up with 3 protons and 4 neutrons, the mass being 7 units and the charge 3 units. Hence there will be 3 planetary electrons and the atom will be neutral. Fig. 5 shows this pictorially, the nucleus representing that of the lithium atom. Take again the case of beryllium, which has 4 planetary electrons and atomic weight 9. Its nucleus can be built up with 4 protons, each carrying a positive charge, and 5 neutrons, each with practically the same mass as that of a proton, but carrying no electrical charge. In the same way it is possible to visualize the nuclei of all the atoms from hydrogen to uranium.

Stable Arrangements of Electrons

It has been shown that the electrons are arranged round the nucleus at various distances and that they are not necessarily in the same plane. They revolve round the nucleus, which attracts them, not in accordance with the universal law of gravitation, but because the nucleus has one or more positive charges associated with it. It is these positive charges, not the nucleus itself, which are responsible for exercising an attraction on the electrons and making them revolve. The electrons are not arranged round the nucleus in a haphazard manner; there are certain configurations which are "closed" and others which are "open", and the following can be taken as a rough outline of the configurations met with in atomic structure. (The words "stable" and "unstable", in a restricted sense, will be used in describing these closed and open configurations, respeetively.)

When two electrons revolve in a shell round the nucleus, this constitutes a stable arrangement, as in the case of helium, but as hydrogen has only one electron outside its nucleus its configuration is not stable. In the next ring or shell, going outwards from the nucleus, there should be 8 electrons for stability, and outside these again, proceeding to elements that stand higher in the periodic classification (*see* p. 46), the next

shell should also contain 8 electrons. The next shell should contain 18 electrons (*see* Fig. 6), but we need not proceed further with a consideration of the stability of these shells, and shall now illustrate what has been said by dealing with a few well-known chemical reactions.

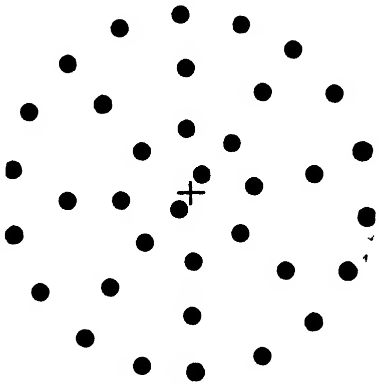

FIG. 6.
Stable arrangements of electrons round the nucleus take place when the numbers of electrons in the outer rings are 2, 8, 8, 18, and so on.

EXPLANATION OF CHEMICAL ACTION

We have already spoken about sodium chloride, or common table salt, which is composed of the soft metal sodium and the gas chlorine. When these two are brought in contact a reaction quickly takes place, the reason for which will be seen by studying Fig. 7.

It should be pointed out first of all that the chemical properties of an element depend very largely on its outer electrons, not on those which are closer to the nucleus, and hence we shall deal mainly with the former. The figure shows an atom of chlorine and one of sodium, the outer shell of the chlorine atom having 7 electrons and that of the sodium atom having only 1 electron. It has been shown that neither of these atoms is in a stable condition, the outer shell of chlorine containing one electron short of the requisite number for stability and that of

sodium containing one too many for stability. Hence when these two atoms approach each other an interaction takes place which is mutually beneficial—if the expression can be used in dealing with such particles. The atom of chlorine is anxious to secure an extra electron to produce stability and the atom of sodium is equally anxious to discard its superfluous electron, the result of which is that the sodium electron passes over to the chlorine atom and the two atoms combine to form a molecule of sodium chloride. It should be noticed that the superfluous electron in the sodium atom gives this atom a nega-

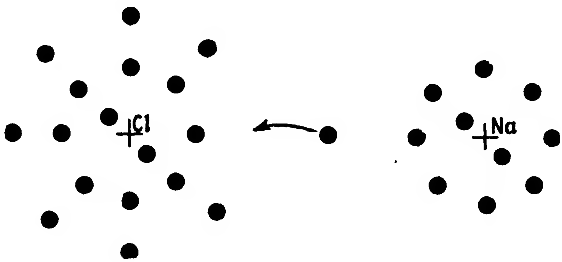

FIG. 7.

The outer shell of the chlorine atom has 7 electrons and hence is unstable. The outer shell of the sodium atom, having only 1 electron, is also unstable. The chlorine atom becomes stable by annexing the single outer electron of the sodium atom, and at the same time the sodium atom, now possessing 8 electrons in its outer shell, becomes stable. By the union of the two atoms sodium chloride is formed.

tive charge, and the lack of the electron in the chlorine atom gives it a positive charge, so that there is an attraction between the two atoms when they are brought close together.

The same reasoning applies to hydrogen and oxygen. We have seen that the hydrogen atom has only 1 electron and hence is in a condition of instability. The atom of oxygen has 8 electrons, the first shell nearest to the nucleus containing 2 and the next shell 6, but as 8 electrons are required in the second shell if stability is to be ensured, the oxygen atom must have 2 more electrons to complete its second shell. As there is only 1 electron associated with the hydrogen atom, this is insufficient to satisfy the oxygen atom, but if 2 hydrogen atoms approach 1 atom of oxygen, the outer shell of the latter will seize the 2 electrons to produce stability, and

hence 1 atom of oxygen unites with two atoms of hydrogen to form water.

This view of the arrangement of the electrons also shows why certain elements do not readily combine with certain other elements. Thus hydrogen wants to get rid of its electron and the same is true of sodium, which has one electron in its outer shell, so there is no tendency for these two atoms to combine. Fig. 8 shows why chlorine and oxygen do not easily* combine. This view of the atom also explains why certain elements will not combine readily with any other element, as, for example,

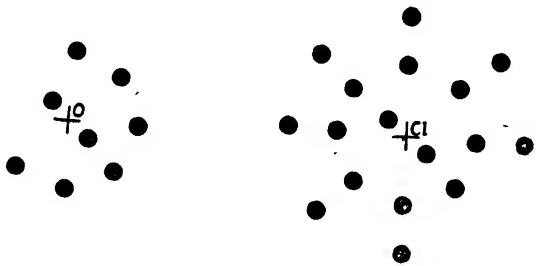

FIG. 8.

The atom of chlorine requires 1 electron, and the atom of oxygen requires 2 electrons, in their outer shells for stability. Hence, as each cannot easily supply the needs of the other, chlorine and oxygen do not readily enter into a stable combination.

in the case of the inert gases, helium, neon, krypton, etc. As the helium atom has 2 electrons in its outer and only shell, it is in a condition of stability and is not able to give or take very readily. The atom of neon has 8 electrons, and the same is true of krypton, in their outer shells, and hence they are stable and remain chemically inert.

THE POSITRON

We have dealt with three elementary particles—the proton, the neutron, and the electron—but others have been discovered, one of which is of some importance when we come to consider

* Chlorine and oxygen can be made to combine to form several oxides of chlorine, but these are extremely unstable, some of them exploding violently by mere contact with other compounds, or even by mechanical shock. As the combinations of chlorine and oxygen are not stable, the statement above that they do not easily combine is substantially correct.

the disintegration of the nucleus of the atom (*see* p. 79). This particle is known as the *positron*, or *positive electron*.

It was reasonable to believe that there should be a positive electron with opposite charge to the negative electron, but for many years it was impossible to find it. In 1925 a distinguished physicist named Dírac proposed a theory of the electron which suggested the existence of a positive particle with properties similar to those of the electron, and in 1932 it was discovered by Anderson while he was investigating cosmic rays (*see* p. 77). Since then it has also been found in artificial radio-activity, which is dealt with in *Chapter VI*.

The positive electron or positron is always accompanied by the ordinary negative electron—known simply as "the electron", and possesses an extraordinary instability, unlike the electron. It seems to be produced along with the electron, but its life is short—about 10^{-8} second—and when it combines with the electron the masses of both arc annihilated. Now it has been shown by the relativity theory that if matter is destroyed a certain amount of energy is released, and it makes no difference in what form the matter has existed; it may be an element or a compound; it may be an electron and a positron; the energy released depends entirely on the *mass* annihilated.

If the electron and the positron combine and annihilate each other, why is it that we do not become aware of the energy released? The answer is that we do become aware of it because it appears asr adiation in the form of γ-rays. The energy equivalent when the electron and positron cancel each other's existence and give rise to γ-rays is dealt with in *Appendix VII*.

Atomic Number

It is necessary to distinguish carefully between the atomic number of an element and its atomic weight. A brief description of the latter has been given on pp. 16–22, and though a certain relation exists between the atomic weight and the atomic number of the elements up to a point, it must not be assumed that one can always be derived from the other.

The atomic number shows the number of positive charges in the nucleus, and this is always the same as the number of planetary* electrons in the atom. Neutrality can exist only

* As the nucleus can be considered to be built up of protons and neutrons, nuclear electrons being unnecessary, "planetary" will not be used in the future.

when this last condition is fulfilled, and hence in the table given on p. 46, where the figures immediately following the symbol for the element denote the atomic number, these will always be equal to the sum of the figures given in the other lines, the latter figures showing the distribution of the electrons. It will be seen from this table that the atomic numbers run consecutively from hydrogen to uranium, and if the atomic number is doubled in the elements from hydrogen to calcium the result is approximately, or often exactly, the atomic weight of the element. After this the rule cannot be applied; thus the atomic weight of scandium is 44, which is more than twice its atomic number, and the atomic weight of lead is 207, which is much larger than twice its atomic number.

Summary of Results

A summary of the results obtained so far may be helpful.

Starting with the simplest of all atoms—that of hydrogen—this consists of a relatively massive central body—the nucleus—which carries one charge of positive electricity and is attended by 1 electron revolving round it in a circle or an ellipse. The distance of the electron from the nucleus varies according to circumstances which will be considered later, but under normal conditions this distance is about $\frac{1}{2} \times 10^{-8}$ cm.

The mass of the nucleus is about 1,844 times that of the electron, and the mass of the latter is 8×10^{-28} gm. Practically all the mass of an atom is contained in its nucleus.

An atom which gains or loses one or more of its electrons is said to have been ionized or to have become an ion. When it gains an electron it has an additional negative charge and when it loses an electron it has an additional positive charge. The hydrogen atom which has lost its one electron and which is then an ion has been given a special name—the proton.

Other elementary particles besides the proton and electron have been discovered, amongst which may be noticed the positron and the neutron, and in the nuclear structure of atoms other than hydrogen the neutron plays a very important part. The neutron has practically the same mass as the proton but is electrically neutral, not carrying a positive or negative charge. Although the structure of the nucleus is not yet fully known, a simple conception of it is that it is made up of protons and neutrons, the former capable of carrying one positive charge

each. The sum of the protons and neutrons gives the atomic weight of the atom, and the number of protons, which is equal to the number of electrons revolving round the nucleus, is the atomic number of the element.

The helium atom consists of 2 protons and 2 neutrons in the nucleus, and 2 revolving electrons. The lithium atom consists of 3 protons and 4 neutrons in the nucleus, and 3 electrons. All the atoms can be built up in a similar manner.

The electrons are identical with the cathode rays in the discharge tube and with the β-rays found in radio-active substances. The positive rays in the discharge tube, when hydrogen is used, are hydrogen ions, that is, hydrogen atoms which have lost their one and only electron, and have then a positive charge. The hydrogen ion is usually called the proton. If helium is used in the discharge tube the positive rays are alpha-particles (generally demoted by α-particles, α being the first letter alpha in the Greek alphabet). The α-particles are emitted by radio-active substances, as will be seen in *Chapter V*.

The chemical (and certain physical) properties of an atom depend almost entirely on the outer shell of electrons. Certain numbers of electrons in the outer shells are necessary for the stability of the atom, and when the requisite number is not present the atom readily combines with certain other atoms to form a chemical compound. When the number of electrons in the outer shell is complete for stability, the atom does not readily combine with any other atoms.

Standard Atomic Weight

The atomic weights of the elements are a series of numbers indicating the *relative*, not the *absolute*, weights of the atoms of the elements. For practical purposes it is necessary to fix a standard for atomic weights, and this standard was once hydrogen, which was selected because it is the lightest element. In some of the older works on chemistry the atomic weight of hydrogen is still given as 1, but it has been found more convenient to adopt oxygen = 16 as the standard. Nearly all elements form stable compounds with oxygen, whereas very few compounds of the metals with hydrogen are suitable for an atomic weight determination. For this reason, if hydrogen be taken as the standard, it is necessary to find the exact relation between an element and oxygen, and then to calculate its atomic weight on the assump-

tion that the relation between hydrogen and oxygen is known with great accuracy. But this latter determination presents many difficulties—more than are found in the case of many other determinations—and so chemists have considered it better to refer the atomic weights to oxygen = 16 as the standard. Incidentally, by making oxygen = 16 as the standard (which is quite arbitrary, as some of the older chemists took

TABLE V.

NAMES AND SYMBOLS OF THE ELEMENTS IN ORDER OF INCREASING ATOMIC NUMBER

Symbol	*Element*	*Atomic Weight*	*Symbol*	*Element*	*Atomic Weight*	*Symbol*	*Element*	*Atomic Weight*
H	Hydrogen	1·008	Ga	Gallium	69·72	Il	Illinium	
He	Helium	4·003	Ge	Germanium	72·60	Sm	Samarium	150·43
Li	Lithium	6·94	As	Arsenic	74·91	Eu	Europium	152·0
Be	Beryllium	9·02	Se	Selenium	78·96	Gd	Gadolinium	156·9
B	Boron	10·82	Br	Bromine	79·92	Tb	Terbium	159·2
C	Carbon	12·01	Kr	Krypton	83·7	Dy	Dysprosium	162·46
N	Nitrogen	14·01	Rb	Rubidium	85·48	Ho	Holmium	164·94
O	Oxygen	16·00	Sr	Strontium	87·63	Er	Erbium	167·2
F	Fluorine	19·0	Y	Yttrium	88·92	Tm	Thulium	169·4
Ne	Neon	20·183	Zr	Zirconium	91·22	Yb	Ytterbium	173·04
Na	Sodium	23·00	Nb	Niobium	92·91	Lu	Lutecium	174·99
Mg	Magnesium	24·32	Mo	Molybdenum	95·95	Hf	Hafnium	178·6
Al	Aluminium	26·97	Ma	Masurium		Ta	Tantalum	180·88
Si	Silicon	28·06	Ru	Ruthenium	101·7	W	Tungsten	183·92
P	Phosphorus	30·98	Rh	Rhodium	102·91	Re	Rhenium	186·31
S	Sulphur	32·06	Pd	Palladium	106·7	Os	Osmium	190·2
Cl	Chlorine	35·46	Ag	Silver	107·88	Ir	Iridium	193·1
A	Argon	39·94	Cd	Cadmium	112·41	Pt	Platinum	195·23
K	Potassium	39·10	In	Indium	114·76	Au	Gold	197·2
Ca	Calcium	40·08	Sn	Tin	118·7	Hg	Mercury	200·61
Sc	Scandium	45·10	Sb	Antimony	121·76	Tl	Thallium	204·39
Ti	Titanium	47·90	Te	Tellurium	127·61	Pb	Lead	207·21
V	Vanadium	50·95	I	Iodine	126·92	Bi	Bismuth	209·0
Cr	Chromium	52·01	X	Xenon	131·3	Po	Polonium	210·0
Mn	Manganese	54·93	Cs	Caesium	132·91	Rn	Radon	222·0
Fe	Iron	55·85	Ba	Barium	137·36	Ra	Radium	226·05
Co	Cobalt	58·94	La	Lanthanum	138·92	Ac	Actinium	227·0
Ni	Nickel	58·69	Ce	Cerium	140·13	Th	Thorium	232·12
Cu	Copper	63·57	Pr	Praseodymium	140·92	Pa	Proto-actinium	231·0
Zn	Zinc	65·38	Nd	Neodymium	144·27	U	Uranium	238·07

values 1, 10 and 100 as standards for oxygen), the minimum changes are involved in the numbers which were used when hydrogen = 1 was the standard.

For other reasons it is fortunate that hydrogen is no longer the standard unit for atomic weights. The atomic weight of each isotope, to a fairly high degree of accuracy, is a whole number, but hydrogen is the most marked exception to the rule, being about 8 in 1,000 heavier than unity. When the proton forms part of a complicated nucleus, as in the heavier elements, it has less mass than when it exists by itself as the nucleus of hydrogen. This difference in mass, explicable on the

relativity view, implies that when protons combine to form a complicated nucleus a certain amount of energy is liberated, mass and energy being practically synonymous on the relativity theory. If it were possible to transform the nucleus of an element whose atomic weight is a little more than an integer into nuclei whose weights were slightly under the integral value, enormous amounts of energy would be released. This is dealt with later (*see* p. 73).

The atomic weights given in Table V are those recommended by the International Committee on Atomic Weights. While these are the most recent figures, it must be remembered that more refined methods may be employed which can imply changes—though of a very minute nature.

Owing to the extremely small quantities of masurium and illinium that have been isolated, their atomic weights have not been determined with great accuracy.

Table VI is taken from *The Nature of the Atom*, by G. K. T. Conn, and is identical with that of Mendeléeff in his work on the relations between the elements. The chief points that the reader should notice are as follows:

After the symbol for each element a number appears in the same line, and this is known as the atomic number. It denotes the number of positive charges in the nucleus. The lower line shows the distribution of the electrons, and the sum of the figures in this line gives the total number of electrons revolving round the nucleus. This number must be equal to the number of positive charges in the nucleus, and hence the sum of the figures in the lower line (or lines in some cases) is always equal to the number in the top line. The last figure in the lower line shows the number of electrons in the outer shell and thus provides an indication of the chemical and physical properties of the atom.

Take the case of calcium, which is followed by the figure 20. This means that its atomic number is 20, or that the nucleus of its atom has 20 positive charges. The other figures show that the electrons are arranged in shells around the nucleus as follows. In the first shell there are 2 electrons, in the second 8, in the third 8, and in the fourth 2. On referring to Table V it will be seen that the atomic weight of calcium is 40, and as its atomic number is 20, implying 20 positive charges on the nucleus, then since each proton has one positive charge there must be 20 protons in the nucleus of calcium. To make the atomic weight 40 there must also be 20 neutrons. In this case

TABLE VI.

THE PERIODIC CLASSIFICATION AND ELECTRONIC STRUCTURE OF THE ELEMENTS

Column / *Row*	0	1	2	3	4	5	6	7	8	9	10
1		H 1 1									
2	He 2 2	Li 3 2, 1	Be 4 2, 2	B 5 2, 3	C 6 2, 4	N 7 2, 5	O 8 2, 6	F 9 2, 7			
3	Ne 10 2, 8	Na 11 2, 8, 1	Mg 12 2, 8, 2	Al 13 2, 8, 3	Si 14 2, 8, 4	P 15 2, 8, 5	S 16 2, 8, 6	Cl 17 2, 8, 7			
4 A	A 18 2, 8, 8	K 19 2, 8, 8, 1	Ca 20 2, 8, 8, 2	Sc 21 2, 8, 9, 2	Ti 22 2, 8, 10, 2	V 23 2, 8, 11, 2	Cn 24 2, 8, 13, 1	Mn 25 2, 8, 13, 2	Fe 26 2, 8, 14, 2	Co 27 2, 8, 15, 2	Ni 28 2, 8, 16, 2
4 B		Cu 29 2, 8, 18, 1	Zn 30 2, 8, 18, 2	Ga 31 2, 8, 18, 3	Ge 32 2, 8, 18, 4	As 33 2, 8, 18, 5	Se 34 2, 8, 18, 6	Br 35 2, 8, 18, 7			
5 A	Kr 36 28, 18, 8	Rb 37 2, 8, 18, 8, 1	Sr 38 2, 8, 18, 8, 2	Y 39 2, 8, 18, 9, 2	Zr 40 2, 8, 18, 10, 2	Nb 41 2, 8, 18, 12, 1	Mo 42 2, 8, 18, 13, 1	Ma 43 2, 8, 18, 14, 1	Ru 44 2, 8, 18, 15, 1	Rl 45 2, 8, 18, 16, 1	Pd 46 2, 8, 18, 18,
5 B		Ag 47 2, 8, 18, 18, 1	Cd 48 2, 8, 18, 18, 2	In 49 2, 8, 18, 18, 3	Sn 50 2, 8, 18, 18, 4	Sb 51 2, 8, 18, 18, 5	Te 52 2, 8, 18, 18, 6	I 53 2, 8, 18, 18, 7			
6 A	Xe 54 2, 8, 18, 18, 8	Cs 55 2, 8, 18, 18, 8, 1	Ba 56 2, 8, 18, 18, 8, 2	La to Lu 57–71	Hf 72 2, 8, 18, 32, 10, 2	Ta 73 2, 8, 18, 32, 11, 2	W 74 2, 8, 18, 32, 12, 2	Re 75 2, 8, 18, 32, 13, 2	Os 76 2, 8, 18, 32, 14, 2	Ir 77 2, 8, 18, 32, 15, 2	Pt 78 2, 8, 18, 32, 16, 2
6 B		Au 79 2, 8, 18, 32, 18, 1	Hg 80 2, 8, 18, 32, 18, 2	Tl 81 2, 8, 18, 32, 18, 3	Pb 82 2, 8, 18, 32, 18, 4	Bl 83 2, 8, 18, 32, 18, 5	Po 84 2, 8, 18, 32, 18, 6				
7 A	Rn 86 2, 8, 18, 32, 18, 8		Ra 88 2, 8, 18, 32, 18, 8, 2	Ac 89 2, 8, 18, 32, 18, 9, 2	Th 90 2, 8, 18, 32, 18, 10, 2	Pa 91 2, 8, 18, 32, 18, 11, 2	U 92 2, 8, 18, 32, 18, 12, 2				

the protons and neutrons are equally divided, but this does not always take place. Thus, the atomic number of silver (Ag) is 47, and hence the nucleus of a silver atom, carrying 47 positive charges, must have 47 protons. The atomic weight of silver is 107·88, which can be taken as 108, and hence there must be $108 - 47 = 61$ neutrons in the nucleus of the silver atom.

Notice that the silver atom has 1 electron in its outer shell and hence is unstable. If it could get rid of this electron it would be stable with 18 electrons in its next shell. The atom of bromine (Br) has 7 electrons in its outer shell and is also unstable, requiring 8 electrons to make it stable. The bromine atom is as anxious to secure another electron as the silver atom is to get rid of its superfluous one, so that it will have only 18 electrons in its outer ring, this arrangement constituting stability. This explains why an atom of silver and an atom of bromine so readily unite to form a molecule of silver bromide.

Chapter IV

SPECTROSCOPIC EVIDENCE FOR THE CONCEPTION OF THE ATOM

The secrets of the structure of the atom have been partly revealed by the theorizing of the mathematician and physicist and also by observational evidence, in particular by means of the spectroscope.

The Spectroscope

When the light from the sun passes through a prism it is broken up into the different colours of the rainbow—violet, indigo, blue, green, yellow, orange and red. The spectroscope is an instrument for effecting this *dispersion* of the colours, as it is called, not only of sunlight but of any kind of light. The principle adopted is the same as that used when an ordinary prism breaks up sunlight, and Fig. 9 shows a simple form of spectroscope. The rays of light from a source on the left side of the diagram pass through a narrow slit and then fall on a convex lens which is so placed that the rays emerge from it in a parallel bundle. These rays then pass through a prism which refracts each colour by a different amount, or, in other words, the prism

disperses the rays into a spectrum which can be examined by a telescope or focused on a plate by a photographic lens. The spectrum in the latter case can then be examined at leisure and much more accurate results can thus be obtained than when it is examined by the telescope.

This is the principle of the spectroscope, but great improvements have been made in recent times, and a grating ruled at very short intervals—14,000 to the inch in some cases—takes the place of the prism and gives better results. We are not concerned with these modifications but primarily with the principle of the instrument and its application to the study of the atom.

The spectroscope shows that the light from a glowing gas

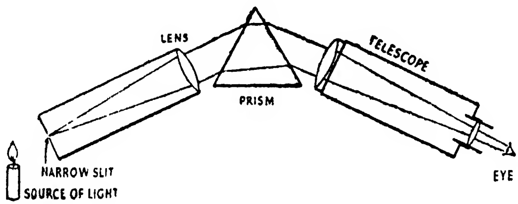

FIG. 9.

The spectroscope is used for studying the spectra of the stars and other bodies, and also the lines emitted by various bodies in the laboratory. Its use has thrown much light on the structure of the atom. See text for explanation.

is of two kinds. There is the first sort due to the molecules of the gas, and named the "band spectra", with which we are not now concerned. The second sort, named the "line spectra", is due to the atoms of the gas and is of great importance in connection with our knowledge of the structure of the atom.

When a gas is glowing its spectrum shows a number of bright lines which are known as the emission-spectrum. If white light is passed through the same gas when it is not glowing, the spectroscope shows that there are dark lines which are largely identical in positions with the bright lines observed in the emission spectrum. These dark lines are called the absorption spectrum, because the non-glowing gas absorbs portions of the emission spectrum. The spectroscopist knows the characteristic spectrum of every element and is able to provide us with a considerable amount of information about the nature of the elements in the outer portions of the sun and other stars.

It is interesting to know that most of the elements found in the stars are the same as those that exist on the earth, thus showing the unity that prevails in the universe.

The application of the spectroscope to the study of the elements in the stars is extremely important, but equally important is its application to the study of the lines emitted by various elements in the laboratory, and this study has thrown much light on the structure of the atom.

Sound-Waves

Most people know that sound consists of wave-condensations and rarefactions in the molecules composing the medium which conducts the sound. These waves are longitudinal; that is, they are in the direction of the propagation of the sound and they can be compared to the movements of a spiral spring which is extended and compressed rapidly. The wavelength of sound is the distance that the pulse has travelled while the particles of air or other medium go through a complete cycle of changes, from the extreme compression to the extreme rarefaction and back again to extreme compression. A useful analogy is found in sea waves, the wavelength being the distance from crest to crest. In normal conditions of temperature and atmospheric pressure the velocity of sound is about 1,100 feet per second, and hence if a note is emitted by 256 vibrations, to and fro, in a second, the distance that sound travels during one vibration is 1,100/256, or about 4·3 feet. This is the *wavelength* of the note and it obviously is smaller the higher the pitch. Thus, if the number of vibrations per second is 512, the wavelength is 1,100/512, or 2·15 feet, and so on. We have dealt with sound-waves first to make the explanation simpler, because when we consider light-waves we shall find that their wavelengths are so minute that it is difficult for the mind to grasp the significance of the figures expressing them.

Light-Waves

Light-waves differ from sound-waves by being what is called "transverse"; that is, they are not in the direction of propagation of the light, but at right angles to it. An illustration is seen by shaking one end of a rope, the other end and most of the rope lying on the ground. The waves which run along the

rope are not in the direction of propagation of the wave but more or less at right angles to it. It is not important for our present purpose to deal with the direction of the light-waves; we are concerned mainly with the wavelengths.

Just as we find the wavelength for a note of any particular pitch by dividing the velocity of sound by the number of vibrations per second, so we find the wavelength of any particular colour by dividing the velocity of light—the same in empty space for all colours—by the number of vibrations per second.

The most recent determination of the velocity of light shows that this is 186,271 miles, or 299,774 kilometres, per second in empty space, but it is generally less in a transparent body. It is usual to express the velocity of light in the metric system, and, as a very close approximation, this is 3×10^{10} cm. per sec. If this number is divided by the number of vibrations per second executed by any point in the medium—the "aether" (which has been postulated for the purpose of transmitting light-waves, but it may not exist), the result is the wavelength. The number of vibrations executed per second is called the frequency, which is, of course, smaller the longer the wavelength. For red light the frequency is about 43×10^{13} and hence the wavelength of red light is $(3 \times 10^{10})/(43 \times 10^{13}) = 7 \times 10^{-5}$ cm. In the case of violet light the frequency is about twice that of red light and hence the wavelength is about half that of red light. There is a very large range of wave-lengths and frequencies, from the long waves used in radio communication, which may be 10^{6} cm., to waves as short as 10^{-9} cm. in X-rays. Table VII shows the wavelengths and frequencies for a number of different forms of radiation.

The Hydrogen Spectrum

A large number of lines is found in the spectrum of hydrogen and many years were spent in attempting to find some kind of connection between them. It was not until 1908, when Ritz formulated his Combination Principle, as it is called, not on theoretical grounds, but from observational evidence, that a connection was found. This principle is explained in *Appendix VIII*.

Under appropriate conditions hydrogen can be caused to emit radiation like other substances, and it can also be caused to absorb radiation. In the latter case, when radiation is passed through the gas in which the hydrogen atoms are present,

radiation of particular frequencies is absorbed, other radiation of different frequencies passing through. This affords an explanation of certain dark lines, due to hydrogen, in the spectra of the sun and other stars.

In both cases—when hydrogen emits or absorbs radiation—the lines corresponding to the series shown in *Appendix VIII* are observed, and this fact supports the view that Ritz's Combination Principle is of fundamental importance in studying the spectra of the hydrogen atom.

No valid reason was given for Ritz's Combination Principle until the matter was taken up by Niels Bohr, a Danish student, working under Rutherford.

Bohr's Hypothesis

Bohr adopted the hypothesis that when a hydrogen atom emits light its electron suddenly jumps into a different orbit which is closer to the nucleus. A certain amount of energy is lost by the atom in these circumstances and this energy is spread out through the surrounding medium in the form of light-waves. If the electron is moved into a larger orbit by the action of external forces, say by the absorption of light, then when these forces are removed it tends to return to the smaller orbit. In doing so it emits energy, and this sometimes appears in the well-known phenomenon of fluorescence, which is caused by the atom emitting light of a certain frequency after it had absorbed light of the same or greater (but not less) frequency.

There is a strict limit to the number of orbits in which the electron can move. It cannot revolve round the nucleus in one case at a distance $0{\cdot}5 \times 10^{-8}$ cm., and then at a distance $0{\cdot}6 \times 10^{-8}$ cm., etc. In fact, when it jumps into another orbit from its smallest possible circle, with a diameter 10^{-8} cm., its next orbit is four times this diameter, and if it leaves this one to move into a larger orbit the next one will have a diameter nine times the first one, and so on. We see the series of square numbers, 4, 9, 16, 25, etc., that are used in finding the formulae for the hydrogen spectrum, as shown in *Appendix VIII*.

Stationary Orbits

The least energy possessed by the atom occurs when the electron is in its smallest orbit, and the greatest energy when

it is in its largest orbit. An electron can move in an orbit without radiating; such an orbit is known as a "stationary" orbit, and outside energy is necessary to make it jump into larger orbits. This energy may be supplied by a positively electrified atom passing near it and attracting it out of its normal course, or it may be supplied by another electron repelling it, or light-waves may drive it out of its course. When the electron is moving in a larger orbit (no orbit need be a circle, it can be an ellipse) it is not in a stable condition and does not require any energy to make it jump back to a smaller orbit. When it jumps back to a smaller orbit it emits light and the nature of the light can be determined from the formulae given in *Appendix VIII.* Thus, suppose it jumps from radius 9 to radius 4, then it emits radiation and, as is seen, the lines with the wave numbers of the first series are revealed by the spectroscope. Hence in the first series $n = 3$ and the frequency corresponding to this is 457×10^{12}. If it jumps from the radius 4 to the smallest radius, 1, it also emits radiation, and as n is 2 in this case, in the second expression the table shows that the frequency is $2{,}468 \times 10^{12}$. The same method applies when radiation is absorbed.

Although the Bohr model gave a good explanation of a number of phenomena connected with the hydrogen atom, especially with certain modifications introduced by Sommerfeld, it failed to explain other phenomena, and since 1925 it has been superseded. It has done very useful work, however, and the Bohr theory is still frequently used for rough and ready purposes of reference. It is very easy to visualize the Bohr concepts, but practically impossible to visualize those in the newer theories. For this reason a short description of Bohr's atom has been given, and there is no reason why it should not be used as a simple conception of the behaviour of the atom.

Difficulties in Applying the Bohr Conception to Atoms other than Hydrogen

It should be pointed out that it was practically impossible for the mathematician to work out all the complexities that arose when Bohr's conceptions were applied to atoms other than hydrogen. The introduction of more than one electron added considerable difficulties to the problem, for reasons with which it is unnecessary to deal. Although the mathematics involved in the theory of the hydrogen spectrum is comparatively simple,

yet Bohr's theoretical results, showing such remarkable agreement with observational evidence, must be considered a wonderful triumph, in spite of the fact that modifications in his original theory were necessary later.

For the primary purpose of this book it is unnecessary for the reader to trouble very much about the results discussed in the present chapter, because they have only an indirect bearing on the main problem which still puzzles the physicist—the structure of the nucleus. Whatever changes may occur in the outer shells of electrons, if the nucleus of the atom remains unchanged the atom is still the same as it was before the jumps of the electrons from one orbit to another. However, the nucleus does not present the impregnable wall to transmutation into the nucleus of another atom that was once believed to exist, and the dream of the alchemist has been realized within the last few decades, though the final product of the transmutation is not gold but—lead.

Wavelengths and Frequencies for Different Kinds of Radiation

Table VII

Wavelengths and Frequencies for Different Kinds of Radiation

Nature of Radiation	*Wavelength in cms*	*Frequency*
Electric waves ..	From 10^{6} to 10^{-2}	From 3×10^{4} to 3×10^{12}
Infra-red waves ..	From 10^{-1} to 10^{-4}	From 3×10^{11} to 3×10^{14}
Visible light ..	From 10^{-4} to 10^{-5}	From 3×10^{14} to 3×10^{15}
Ultra-violet rays	From 10^{-5} to 10^{-7}	From 3×10^{15} to 3×10^{17}
X-rays	From 10^{-6} to 10^{-9}	From 3×10^{16} to 3×10^{19}
γ-rays	From 10^{-8} to 10^{-11}	From 3×10^{18} to 3×10^{21}

The frequencies given in the third column are deduced from the wavelengths by dividing the latter into 3×10^{10}, which is the speed of light in cms. per second. Thus if the wavelength of the infra-red waves is taken as 10^{-4} cm., the corresponding frequency is $3 \times 10^{10}/10^{-4} = 3 \times 10^{14}$.

The regions have no very sharp boundaries, X-rays over-

lapping ultra-violet on one side and gamma-rays, usually called γ-rays (γ is the symbol for the Greek letter gamma) on the other, and the same thing occurs for other waves. It is quite possible that other rays may be discovered, and hence it must not be assumed that the limits have necessarily been reached at either end of the wavelengths. It will be seen that the range for visible light is very narrow—from about 10^{-4} cm. to 10^{-5} cm. In spite of the enormous difference between the extremes—the frequency of the X-rays is about 10^{15} times that of the longest electric waves—all the radiations are essentially of the same nature. If we wish to assume that they are simply vibrations in the "aether of space" we can do so, but there may be no "aether of space", and even if there were it is irrelevant for our present purpose to discuss the various views propounded regarding its characteristics.

Chapter V

RADIOACTIVE SUBSTANCES

THE discovery of radioactivity, like many other discoveries, was largely due to accident, though if the accident had not happened to Henri Becquerel in 1896 it is certain that the discovery would have taken place very soon afterwards. Becquerel, professor of physics at Sorbonne, was interested in fluorescence (*see* p. 51), and in 1896 he was studying this phenomenon in uranium bisulphate when his work was interrupted by some other interests, and he placed the uranium bisulphate in a drawer which fortunately contained some photographic plates. There was no deliberate intention of placing the uranium amongst these plates, but this mere accident expedited an important discovery.

URANIUM EMANATIONS

After some weeks Becquerel opened the drawer and took out the plates from their box on the top of which he had thrown the uranium compound, and developed the photographs. He then found that the plates had been spoiled as if they had been previously exposed to light, but this seemed impossible because

they had been wrapped in thick black paper and no light had been allowed to interfere with them.

Becquerel suspected that the uranium bisulphate had emitted some invisible and highly penetrating radiation that passed through the box in which he had placed the uranium, and had penetrated the thick covering round the photographic plates. He repeated the experiment and placed an iron key between the photographic plates and the uranium. A few days later when he examined the plates he saw that there was a silhouette of the key against the negative, and he knew that he had discovered a new kind of radiation emanating from the atoms of the uranium which was able to penetrate materials not transparent to ordinary light but was unable to penetrate the iron key.

Effects of Uranium Emanations

It was soon discovered that compounds of uranium had other effects besides fogging photographic plates. Screens coated with certain minerals such as zinc fluoride became luminescent when placed near the uranium compounds, and a charged electroscope lost its charge. The rate of discharge of the electroscope could even be used to measure the amount of radioactive substances present.

Discovery of Radium and other Radioactive Substances

Other radioactive elements were soon discovered and the Curies were pioneers in this research. In 1898 Mme Curie found that pitchblende, an ore which is the oxide of uranium, was much more active than was to be expected from its known content of uranium, and she succeeded in extracting two previously unknown elements with higher radioactivity than uranium. One of these was called radium and the other polonium, after her country. Some time afterwards one of the collaborators of the Curies discovered another radioactive element which was named actinium. It was not until 1910 that a long series of experiments ended with the isolation of metallic radium by electrolysis, and this very precious element has received a large number of important applications in various directions, not least for medicinal purposes.

More than forty radioactive elements are now known, but

most of them are so rare that they have never been isolated in visible amounts and are recognized only by their radioactive effects. Three types of rays are emitted by radioactive substances, and a brief reference to two of these has already been made (p. 31). The third type, known as the γ-rays, are electromagnetic radiation of very short wavelength—less than 10^{-8} cm. They are the most penetrating of all radiation except cosmic rays (*see* p. 77), but it is not necessary to dwell on their properties, as our chief interest is with the α- and β-rays.

A table showing the uranium, thorium and actinium series is given on pp. 58–9. It will be seen from this that there is a very wide range in the period required for the disintegration of half the mass (*see* p. 60) of the various radioactive substances, thorium requiring over 10^{10} years and thorium C′ 10^{-11} second.

Disintegration of the Atom

In 1902 Rutherford and Soddy suggested that radioactivity was due to the atoms of the elements decomposing and giving place to another element, the process being repeated until the final product was stable. While this suggestion was rather startling at the time, it was supported by evidence from the behaviour of thorium nitrate; this compound gives off an emanation which behaves as a gas, and, following a simple chemical reaction, a very important discovery was made.

To a solution of thorium nitrate they added ammonium hydroxide, and the thorium hydroxide which was precipitated had very little radioactivity. The filtrate (the liquid remaining after the precipitate had been separated from it) contained a very active substance to which the name thorium-X was given. After the lapse of a month the thorium-X had completely lost its activity, but the precipitate of thorium hydroxide had recovered the activity of the original thorium nitrate. During the time that the precipitate was recovering its activity it was found that the total activity, obtained by taking the sum of the activities of the filtrate and the precipitate, remained a constant, and the interpretation of the phenomena observed will be better understood by referring to Table VIIIB on p. 59.

Thorium disintegrates very slowly, its half-value period being $1{\cdot}3 \times 10^{10}$ years, and produces mesothorium$_1$, whose half-value period is only 6·7 years. It is seen from the table that α-rays are emitted in this disintegration, and it has

been observed that these are identical with the nucleus of helium whose atomic weight is 4, so the atomic weight of the product should be $232{\cdot}12-4 = 228{\cdot}12$, but we may ignore the apparent discrepancy of 0·12, knowing the effect of isotopes (*see* p. 23) on the atomic weights of a number of elements. The atomic number drops by 2 because two positive charges have been emitted by the α-rays, and when these disappear the atomic number must be reduced by 2 (*see* p. 41.) Mesothorium$_1$ disintegrates into mesothorium$_2$ and emits β-rays in the process, but as the mass of these is very small in comparison with that of the nucleus, the atomic weight of mesothorium$_2$ is the same as that of mesothorium$_1$, though its atomic number is one more, as might be expected from the loss of an electron, which implies an extra positive charge on the atom. The series can be followed on to the end product—thorium D with atomic weight 208 and atomic number 82, which correspond to an isotope of lead.

Thorium-X is very much more active than thorium but it is soluble in ammonium hydroxide and so is not precipitated like thorium. Hence the more active element, thorium-X, remained in the filtrate, and this, as might be expected, continued active, but not for long. The half-value period is only 3·6 days, so in about a month its activity would have decreased very much, only about one-three-hundredth of the original thorium-X remaining then, but meanwhile the precipitate of thorium hydroxide had recovered the activity which had been lost by the absence of thorium-X, and emanated mesothorium$_1$, which in turn emanated mesothorium$_2$, and so on to thorium-X.

With this theory it was possible to arrange all the radioactive elements in three disintegration series, and it is remarkable that all three end in isotopes of lead. It may be mentioned at this point, though it is not directly connected with the object of this book, that if we assume all the lead found associated with radioactive ores to be radioactive in origin, then from the relative proportions of inactive lead and active uranium it is possible to estimate how long the process has been going on and hence the age of the earth. Although certain assumptions, which cannot be considered quite valid, must be made in the calculations, the results are in fair agreement with those derived by other methods.

The radioactive elements have been arranged in three disintegration series. The first starts from uranium and finally reaches an isotope of lead. The second starts with thorium and

ends with another isotope of lead. A third series starts with actinium and also ends with another isotope of lead. Fig. 10 shows radium breaking down into radon and helium.

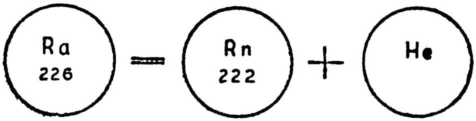

FIG. 10.

Radium breaks down spontaneously into radon and helium—an example of the transmutation of one element into another

TABLE VIIIA

THE URANIUM SERIES

Element	*Atomic Weight*	*Atomic Number*	*Rays Emitted*	*Half-Value Period*
Uranium i	238·07	92	α	$4{\cdot}5 \times 10^9$ years
Uranium X_1	234	90	β, γ	24 days
Uranium X_2	234	91	β, γ	1·2 minutes
*Uranium Z	234	91	β	6·7 hours
Uranium ii	234	92	α	$3{\cdot}4 \times 10^5$ years
Ionium	230	90	α	$8{\cdot}2 \times 10^4$ years
Radium	226·05	88	α, β, γ	$1{\cdot}6 \times 10^3$ years
Radon (Radium Emanation)	222	86	α	3·8 days
Radium A	218	84	α	3·1 minutes
Radium B	214	82	β, γ	27 minutes
Radium C	214	83	α, β, γ	20 minutes
Radium C′	214	84	α	10^{-6} seconds
*Radium C″	210	81	β	1·3 minutes
Radium D	210	82	β, γ	22 years
Radium E	210	83	β, γ	4·9 days
Radium F (Polonium)	210	84	α	$1{\cdot}4 \times 10^2$ days
Radium G (lead)	206	82	inactive	

* Denotes a branching of the series.

TABLE VIIIB

THE THORIUM SERIES

Element	*Atomic Weight*	*Atomic Number*	*Rays Emitted*	*Half-Value Period*
Thorium	232·12	90	α	$1{\cdot}3 \times 10^{10}$ years
Mesothorium$_1$	228	88	β	6·7 years
Mesothorium$_2$	228	89	β, γ	6·1 hours
Radiothorium	228	90	α, β	1·9 years
Thorium X	224	88	α	3·6 days
Thoron (Thorium Emanation)	220	86	α	55 seconds
Thorium A	216	84	α	0·14 second
Thorium B	212	82	β, γ	11 hours
Thorium C	212	83	α, β	61 minutes
Thorium C′	212	84	α	10^{-11} seconds
Thorium C″	208	81	β, γ	3·2 minutes
Thorium D (lead)	208	82	inactive	

TABLE VIIIC

THE ACTINIUM SERIES

Element	*Atomic Weight*	*Atomic Number*	*Rays Emitted*	*Half-Value Period*
Protoactinium	231	91	α	10^4 years
Actinium	227	89	β, γ	20 years
Radioactinium	227	90	α	19 days
Actinium X	223	88	α	11·2 days
Actinium Emanation	219	86	α	3·9 seconds
Actinium A	215	84	α	0·002 seconds
Actinium B	211	82	β, γ	36 minutes
Actinium C	211	83	β, γ	2·16 minutes
Actinium C′	211	84	α	10^3 seconds
Actinium C″	207	81	β, γ	4·76 minutes
Actinium D (lead)		81	inactive	

Although the half-value period for radium is 1,600 years, it is interesting to know that a gram of radium produces 35×10^9 α-particles every second. It is able to maintain this rate of emission for a long time as its mass diminishes only to a very minute extent even after many years.

The Cause of Disintegration Not Known

The nuclei of radioactive elements have a certain tendency towards instability, and it would be most interesting if we could obtain some information about the mechanism which causes the disintegration of the nuclei, but such information is not forthcoming. On first considerations it might seem that age would be a determining factor just as it is in forming an estimate of the expected life of an individual. A man of 60 has less chance of living for 10 years than a man of 40, and on the same principle an atom which was older than another one might be expected to explode or disintegrate sooner. But this does not hold and it seems that pure chance decides what any particular atom will do. In any given interval of time the same fraction of atoms left over will disintegrate. Suppose we start with 1 gm. of uranium X_1, the half-value period of which is 24 days. At the end of 24 days $\frac{1}{2}$ gm. will have disintegrated and at the end of 48 days one-half the remainder will have disintegrated, and so on. The process can be represented by the figures given below in which the amount disintegrated each 24 days is added on to the amount previously disintegrated. The result is the total amount disintegrated.

Original amount	1 gm.
Amount disintegrated in 24 days	$\frac{1}{2}$ gm.
Amount remaining	$\frac{1}{2}$ gm.
Amount disintegrated in 48 days	$\frac{1}{4} + \frac{1}{2} = \frac{3}{4}$ gm.
Amount remaining	$\frac{1}{4}$ gm.
Amount disintegrated in 72 days	$\frac{1}{8} + \frac{3}{4} = \frac{7}{8}$ gm.
Amount remaining	$\frac{1}{8}$ gm.
Amount disintegrated in 96 days	$\frac{1}{16} + \frac{7}{8} = \frac{15}{16}$ gm.

The process goes on indefinitely, and it will be seen that in theory there will always be some of the element left, though finally it will be too small to be easily detected.

A study of the distribution of the ejected particles shows that these are not only controlled by chance, but also that their

direction of ejection is controlled in the same way. Chemical combinations of the atoms have no effect on their disintegration and no physical processes accelerate or delay the dissolution of the atoms. They seem to be outside the power of human control. If man were able to exercise some influence on the atoms of the radioactive substances and to select those atoms which he knew would soon disintegrate, what a powerful source of energy would be placed in his hands! The information at our disposal at present suggests that we are dealing merely with statistical laws.

Disintegration in Atoms of Lighter Elements

Up to the present we have considered only the very heaviest elements in connection with radioactivity, but this phenomenon is not limited to the heaviest elements. Some of the lighter elements have been found to be very feebly radioactive, amongst which are potassium, rubidium and samarium, the first two emitting β-particles and the last α-particles. It is possible that all elements are radioactive, but the great majority to such a very small extent that it is quite impossible to detect their radiation.

Artificial Disintegration of the Atom

Although the spontaneous disintegration of the atoms in the elements referred to is not amenable to human control, it is possible to produce nuclear changes by artificial methods; that is, to transmute atoms of one element into atoms of another element.

In 1919 Rutherford found that particles from radium passing through nitrogen ejected particles which had high speeds, and he showed from their deflection by a magnetic field that they were protons. The reaction, which is called the *nuclear reaction*, can be represented by an equation of the form

$$_2He^4 + {}_7N^{14} = {}_1H^1 + {}_7O^{17}$$

the result being the transformation of the atom of nitrogen into the atom of a heavy isotope of oxygen, a hydrogen nucleus being set free. (The numbers at the top and bottom indicate the atomic weight and atomic number respectively.)

Rutherford and Chadwick examined the behaviour of many of the light elements under α-particle bombardment and found that disintegrations mostly occurred. Others have carried out further experiments with different particles, such as protons and neutrons, and have obtained very interesting results. It must not be thought, however, that when bombardment takes place every α-particle or proton or other particle used in breaking up the atom hits a target, as the results of an experiment to be described soon will show. Before describing the experiment, however, it will be necessary to say a little about fogs.

Condensation of Water Vapour on Nuclei

Everyone knows that air and water vapour will mix, but not to an unlimited extent. There comes a stage when the air will not mix with any more water vapour and we say that the air is then saturated. The point at which saturation occurs depends upon the height of the barometer and also on the temperature. If the barometer suddenly falls the quantity of water which the air is capable of retaining as vapour falls, and the result is that condensation into small drops takes place.

Condensation of the droplets is made much easier if there is dust or soot in the atmosphere, and those who have experienced the inconveniences of a city fog know that it covers everything, human beings included, with a layer of soot. If we had fewer chimneys discharging smoke and grit into the atmosphere we should not suffer so much from fogs, but even if smoke and dust were entirely eliminated fogs would still prevail, though not to such an extent as they do at present.

Ions Can Act as Nuclei

The small particles in the atmosphere form the nuclei on which the water can collect, but it has been found that ions also form the nuclei for condensation. This fact has been utilized in the Wilson Cloud Chamber to make the paths of particles visible. A piston connected to the chamber can be pulled out, lowering the pressure, thus imitating artificially what occurs naturally when the barometer falls before a fog. If the air in the chamber has been purified from dust particles condensation will not take place, but if particles are shot into the chamber,

these form ions along their path and these ions act as nuclei to collect water droplets. In consequence of this the paths of the particles are rendered visible (not the particles themselves) as very fine tracks of fog. These tracks can be observed through a window or photographed, and they afford most interesting evidence about the effect of the bombardment of the atoms and molecules of gas by α- or other particles.

Bombardment of Nuclei by α-Particles

Blackett, one of Rutherford's students, bombarded ordinary air, which contains about 80 per cent of nitrogen, with α-particles and photographed the results in the cloud chamber. As the particles passed through the gas in the cloud chamber they tore off some of the electrons from the atoms, leaving behind a number of ions on which small drops of water from the saturated atmosphere inside the chamber immediately condensed. Very important results were obtained.

The α-particles produced a large number of ions as they passed through the gas, but something more than this was sought for. We have seen that the nucleus of an atom is extremely small in comparison with the atom, and hence many α-particles could pass through the empty space in an atom, attracting the loosely held outer electrons from the atoms to themselves, but missing the nuclei. As a rough analogy we might compare it to firing a shotgun into a large field where we know there is a rabbit, though we do not know what part of the field it is in, and hoping that one of the pellets will take effect.

Blackett took 23,000 photographs and found that eight of these showed direct collisions between α-particles and nuclei. One of these photographs showed an α-particle approaching a nitrogen nucleus and striking it, a proton being ejected sideways, while the main portion of the nucleus was shot to the other side (*see* Frontispiece). The result was just what we might expect if we hurled one body against another which had some portions more or less loosely attached to it. If it were an oblique collision the main portion of the body and the loose pieces would pursue different paths after the impact. In addition to providing information about the directions of the particles before and after impact, the track also provides information about the nature of the

particles, the thickness of the band of fog being a criterion of the amount of ionization and hence of the electric charge carried, from which the nature of the particle, proton, helium, nucleus, etc., can be inferred. It was found that the nuclear reaction was that described on p. 61, nitrogen being transformed into a heavy isotope of oxygen, with the liberation of a proton. (*See* Fig. 11.)

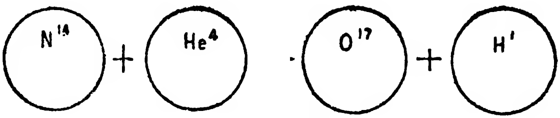

Fig. 11.

When the nucleus of a nitrogen atom is struck by an α-particle, that is, by the nucleus of a helium atom, a hydrogen nucleus (the proton) is liberated and an atom of the heavy isotope of oxygen is formed.

Counting the α-Particles

Screens coated with willemite or other suitable material become luminescent when exposed to cathode rays and a similar effect is produced when α-particles are used. Examination of this latter luminescence shows that it is due to a large number of scintillations, each α-particle producing a flash. An instrument called the spinthariscope was invented by Crookes which shows these effects and also enables the number of α-particles to be counted. Observations of the number of faint flashes are not easily conducted with great accuracy, and different experimenters have obtained different results, for which reason the Geiger counter, invented by Rutherford and Geiger, has been of very great use in advancing our knowledge of the atom.

Although these counters differ in detail according to the particular object to which they are to be applied, their principle is the same and is based upon the fact that the current passed by a source of high potential (about 1,500 volts) through an air space depends upon the number of ions present. The number of ions produced by an α-particle would make very little difference to the passage of the current, but under the action of the high potential the ions attain speeds sufficient to ionize other atoms with which they collide. The result is that the number of ions produced is considerably increased and

hence the observed current is magnified many times. The discharge from the source of high potential is indicated by the kick of a galvonometer, and by introducing a suitable valve relay circuit the momentary discharge can be made to operate an automatic recording apparatus. By this apparatus it is possible to detect the effects of single atomic particles, though the atoms themselves cannot be seen, and the conception of the atom, a brief outline of which has been given in the preceding pages, receives support amounting practically to absolute verification.

Bombardment of Nuclei by Protons

If particles lighter than α-particles—such as protons—are used for the bombardment of atomic nuclei, they will not be repelled with such force when they approach the heavily charged nuclei because they carry a smaller electric charge. As, however, protons are not emitted by the ordinary radioactive elements, if they are to be used for nuclear reactions they must be produced artificially. Cockcroft, a pupil of Rutherford, carried out successful experiments at Cambridge by using a high-tension transformer giving 500,000 volts, and produced a beam of protons moving with a speed of 10,000 kilometres (about 6,200 miles) a second. Although these particles had only one-fourth the mass of the α-particles used by Rutherford, they proved quite effective. When they collided with the nuclei of lithium these broke up into two equal parts, which were shown to be the nuclei of helium. The nuclear reaction is as follows:

$$_3Li^7 + {}_1H^1 \rightarrow {}_2He^4 + {}_2He^4$$

They also transformed nitrogen into carbon and boron into helium, the nuclear reactions being as shown below:

$$_7N^{14} + {}_1H^1 \rightarrow {}_6C^{11} + {}_2He^4$$
$$_5B^{11} + {}_1H^1 \rightarrow {}_2He^4 + {}_2He^4 + {}_2He^4$$

Cockcroft's pioneering work in the production of artificial protons was followed up by others, and a number of physical laboratories in various parts of the world now use some form of apparatus for disintegrating the atom.

Other Methods of Bombarding Nuclei

One of the first things that we learned about electricity was that it resides on the external surface of a conductor, and probably many readers performed the well-known experiment with the hollow insulated sphere with an orifice in the top. When the sphere is charged with electricity and a small piece of gilt paper insulated by a thin handle of shellac is applied to the interior surface of the sphere, it shows no charge. While tests by an electroscope fail to reveal the slightest sign of a charge, if the exterior of the sphere is touched the gilt paper is found to be electrified. Many other similar forms of experiment confirm the fact that electricity resides on the surface—not in the interior—of conductors, and this principle has been utilized in the production of an atom-breaker.

It may be remembered that a hollow sphere could be charged up to a high potential and would give off sparks if one had enough patience to touch the interior a sufficient number of times with a small insulated charged conductor. The generator for the atom-breaker differs from the hollow sphere chiefly in size, though naturally in many details there are differences. The transfer of the charge to the interior of the huge sphere is effected by a system which charges the sphere continuously, and the potential can be raised to 5 million volts in a few minutes. Beams of fast-moving particles of different kinds, protons, α-particles, etc., can be produced by means of this highly charged sphere. One end of a vacuum glass tube enters the charged sphere and the ions from the enclosed gas move to the other end with very high speeds. They are directed toward their targets under investigation and their effect in nuclear disintegration can be studied.

The Cyclotron

A different kind of apparatus was constructed by Dr. Ernest O. Lawrence in California, and was named the cyclotron.* The principle utilized in this instrument is to accelerate the particles at a point in the circular path that they describe so that ultimately they attain a very high speed. If a charged particle is moving in a certain direction and we apply a magnetic field at right angles to its direction of motion it will move

* A short description of a giant cyclotron is given at the end of the chapter.

in a circular orbit. Each time the particle passes a certain point in its track an electric tension is applied, thus increasing its speed. If the speed of a planet in its revolution round the sun were continuously increased by some external force it would move away from the sun in a spiral course. The same thing happens to the particles in the cyclotron; their speed is increased by the external force—the electrical tension—and the radii of their orbits grow larger. After a certain number of

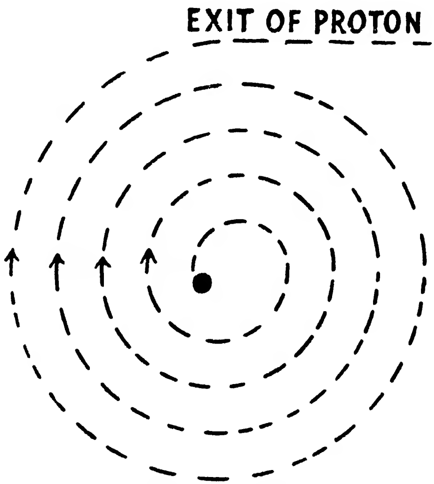

FIG. 12 (Illustrating the principle of the cyclotron).
Particles are accelerated by electric methods and emerge from their spiral paths with high speeds. They then bombard the nuclei of different kinds of atoms.

revolutions the particles emerge through a thin mica window, and can be used to bombard the nuclei of different elements. With the aid of the cyclotron a number of other nuclear reactions, in addition to the few already mentioned, have been studied. (*See* Fig. 12.)

We have already referred to the importance of the discovery of the neutron in simplifying our conception of the structure of the nucleus, but more important still is the application of the neutron to bombarding the atom. A proton penetrates a sheet of lead to a very small extent—a mere fraction of a millimetre—

but it has been found that a neutron moving with the same velocity as a proton can penetrate a sheet of lead 20 cm. thick. The reason for this wonderful penetrative power is apparent from the following considerations.

The proton with its charge of electricity attracts the electrons of atoms which lie in its path and each time that it annexes an electron it loses some of its energy of motion. For this reason it is very quickly brought to rest. On the other hand, the neutron, not possessing a charge of electricity, will not attract or repel the electrons of any atoms that lie near its path, and

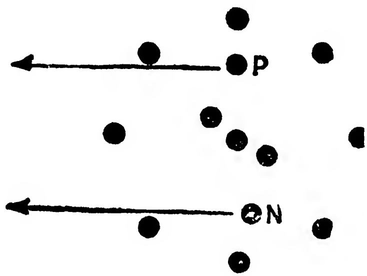

FIG. 13.

A proton P carries a positive charge of electricity and hence attracts the electrons in an atom. The neutron *N* has no charge and hence does not attract electrons, so it does not suffer as many collisions as the proton and is therefore more penetrating.

hence will pass through the skeleton of an atom without losing velocity. A collision with the nucleus of an atom is certain to occur at some point in its path, but as the nucleus is so very small the neutron can travel a comparatively great distance before an encounter with the nucleus takes place. This explains why neutrons penetrate a very much greater thickness of matter than protons, and also explains why they are so dangerous to life unless thick barricades are set up to protect experimenters from the injurious effects which would otherwise result from their penetrative power. (*See* Fig. 13.)

THE HEAVY ISOTOPE OF HYDROGEN

We have already referred to isotopes (*see* p. 23) and mentioned a few common isotopes. One isotope discovered in

comparatively recent times is the heavy isotope of hydrogen, named *deuterium*, for which the symbol D is used. Its charge is 1, like ordinary hydrogen, and hence, as it has only 1 electron, its chemical properties are similar to those of ordinary hydrogen. It differs from ordinary hydrogen in its mass, which is twice that of the hydrogen with which we are conversant. Water containing this heavy isotope of hydrogen is known as *heavy water* and is about 5 per cent. heavier than ordinary water. A still heavier isotope of mass 3 has been discovered to which the name *tritium* has been given. Heavy water is found in various parts of the world, Norway supplying large quantities, and the heavier isotopes of hydrogen can be separated from the lighter by electrolysis (*see* p. 29). The lighter is liberated much more rapidly than the heavier, and by repeating the electrolysis many times in the residual liquid pure "heavy water" is obtained.

The heavy isotope of hydrogen is important because neutrons can be produced by making two of the nuclei of this isotope collide. If the ions of heavy hydrogen are accelerated in the high-tension generator, and then fall on heavy water, a large number of fast-moving neutrons are produced. The nuclear reaction is as follows:

$$_{1}D^{2} + {}_{1}D^{2} \rightarrow {}_{2}He^{3} + {}_{0}n^{1}$$

The light isotope of helium, mass 3, in addition to the neutron, is produced by the collision. (The symbol 0 in n, the neutron, denotes that it has no charge.)

Amongst the effects of neutron bombardment we may notice the following:

$$_{7}N^{14} + {}_{0}n^{1} \rightarrow {}_{5}B^{11} + {}_{2}He^{4}$$

nitrogen being transformed into boron and helium; and

$$_{26}Fe^{56} + {}_{0}n^{1} \rightarrow {}_{25}Mn^{56} + {}_{1}H^{1}$$

representing the transformation of iron into manganese and hydrogen.

When the neutrons encounter the nuclei of the heavier elements they are unable to eject any constituent of the nucleus —neutron or proton—but they may adhere to the nucleus and increase the atomic weight of the element. Thus, when a neutron encounters the nucleus of gold, the reaction is

$$_{79}Au^{197} + {}_{0}n^{1} = {}_{79}Au^{198} + \gamma\text{-rays.}$$

The heavier isotope of gold is produced and γ-rays are emitted in the process.

Developments in Nuclear Bombardment

Many interesting developments have taken place in nuclear bombardment, but it is impossible to deal with all of these, and only a few outstanding points will be referred to.

It might seem that the greater the speed of the bombarding particles the greater would be the probability of disrupting the nucleus, but close examination of the action of neutrons has led to the opposite conclusion. It has been found that when the speed of neutrons is reduced by passing them through hydrogeneous matter, like water and paraffin, their efficiency in nuclear bombardment is greatly enhanced. It is possible to explain this apparent anomaly on the theory that the nucleus has a particular affinity for neutrons of low energy. When a neutron is captured by a nucleus there is formed an isotope of the element with atomic weight greater by one than that of the atom which has captured the neutron, and the extra weight may make the new atom unstable, which, in turn, may result in radioactivity. It is interesting to know that more than 300 new radioactive isotopes have been produced artificially, but it is impossible to predict beforehand what the half-life of any one of them will be.

It was found by Fermi that a neutron could penetrate the uranium nucleus, the heaviest of all known elements, and after the capture of the neutron an electron was given off. This emission of the electron increased the atomic number by one, thus forming a new element with atomic number 93. This new element in turn disintegrates, giving rise to radioactivities which include elements with atomic numbers 94, 95, and 96. These elements, to which the name *trans-uranic* has been given, do not possess the properties of the elements with atomic numbers 86 to 92.

Ten radioactive periods were associated with these new elements and a considerable amount of work was carried out to find out something more about the radioactive family. In 1937 Otto Hahn, a distinguished chemist in Berlin, with his assistants, Strassmann and Miss Meitner, had succeeded in arranging these new elements in three series, but a new element discovered by Madame Curie-Joliot in Paris refused to fit in

with this series. This new element resulted from the bombardment of uranium with neutrons, and when Hahn repeated the experiment towards the end of 1938 he found the element discovered by Madame Curie-Joliot, and also another one which emitted α-particles. This was in strong contrast to what has been previously known in induced radioactivity in which the lighter particles—electrons and positrons—were emitted. A very remarkable feature of the discovery was that Hahn's new element seemed to be an isotope of radium. On referring to Table VIIIA it is seen that radium is formed from uranium ii by the emission of two α-particles, but never before had this process been known to follow the capture of a neutron.

We need not dwell on the details of Hahn's work in investigating the properties of the new activity, and it will be sufficent to say that his researches led to the discovery of the fission of the uranium nucleus, barium and krypton being the result.

Very soon after he had published his views Miss Meitner, who had been exiled from Germany and was working in Copenhagen, announced that she with one of her co-workers had suggested the same view, and they explained the fission on the analogy of a water-drop. When this grows too large it breaks up into two drops, each practically the same size. The addition of one more neutron had just been responsible for making the uranium nucleus unstable. Perhaps one of the most important points in connection with the fission of the uranium nucleus is that enormous amounts of energy are released in the process. This is considerably greater than the energy released by the natural radioactive elements.

It should be said that the experiment has been repeated by others with the same results, and the effects of uranium fission can be seen by means of an instrument known as the oscilloscope, just as the effects of ions can be seen in the Wilson chamber, but in the oscilloscope the effects are much more spectacular, as they are shown on a screen. It must be interesting to see certain effects on the screen which inform the spectators that a neutron beam falling on uranium has caused fission.

Equivalence of Mass and Energy

The energy released when a mass of m gm. disappears in radiation is mc^2 ergs, where c is the velocity of light, that is, 3×10^{10} cm. per sec. Suppose a mass of 1 gm. disappears in

radiation, the energy released is 9×10^{20} ergs, and reducing this to the English system we can say that if 15·4 grains of matter were converted into radiation the energy released would be about 66×10^{12} foot pounds. If this energy were released very rapidly it would have devastating effects, but if it could be released slowly—say over a year—and the energy harnessed, it could drive many of our locomotives for this period. Since a horsepower is equivalent to $7{\cdot}46 \times 10^{9}$ ergs per second, the horsepower latent in a gram of matter is $(9 \times 10^{20})/(7{\cdot}46 \times 10^{9}) = 12 \times 10^{10}$. If we imagine engines with 50,000 horsepower, this energy would keep them running for $(12 \times 10^{10})/(5 \times 10^{4}) = 24 \times 10^{5}$ seconds, or about 28 days. Evidently if we could release at a suitable rate the energy inherent in matter (its nature is of no consequence, solid, liquid or gaseous) we could drive some of our large liners across the Atlantic with the small amount of matter that would lie on the palm of our hand.

It is not necessary to annihilate matter to derive an enormous quantity of energy; by the transformation of one element into another large amounts of energy are released, though not so much as would be released if we could annihilate matter. It has been shown that the collision between lithium and hydrogen nuclei gives rise to two helium nuclei; about $2{\cdot}5 \times 10^{-5}$ erg of energy is released in the process, which seems very small, but an examination of the mass of the atom of lithium will convince us that this amount of energy is not to be despised.

The hydrogen atom weighs $1{\cdot}5 \times 10^{-24}$ gm. and hence the atom of lithium, whose atomic weight is 7, weighs about 10^{-23} gm. This shows that in 1 gram of lithium there are 10^{23} atoms and the total energy in this is 10^{23} times the energy in 1 atom; that is, it is $2{\cdot}5 \times 10^{18}$ ergs. If the transformation took place in a second the effect would be terrific, a total horsepower of over 3×10^{8} being developed. This is about one-four-hundredth of the horsepower developed by the annihilation of a gram of matter, but the transformation even of this energy, if it could be harnessed, would revolutionize our industrial and economic system.

Mass Defects

The masses of the nuclei of various elements exhibit very small deviations from integral values. Thus the atomic weight of helium, 4·002, differs from four times the weight of 1 proton, $4 \times 1{\cdot}0078 = 4{\cdot}0312$, the difference being 0·0292, which does

not seem very much, but in comparison with the mass of a proton it is greater than is found in many other nuclei. This implies that a large amount of energy is required to disintegrate the helium nucleus, because its binding is strong. The small mass of 0·0292 represents an enormous amount of energy. Quantitative results are given in *Appendix VI*, and from these it is obvious why in radioactive disintegration the α-particles, that is the helium nuclei, are ejected whole.

The mass defect is the difference between the sum of the masses of the constituents of the nucleus and the mass of the nucleus which they have formed. The mass defects of the nuclei of all the elements show certain regularities, increasing in passing to elements of higher nuclear charges, but from the middle of the periodic table the rise becomes slower, and as we approach the radioactive elements it falls off rapidly. This explains why the nuclei of the radioactive elements are so unstable and disintegrate spontaneously—unlike those of many other elements, which require artificial methods to disrupt them.

In the case of the heavy isotope of hydrogen the exact mass of the nucleus is 2·0136 and that of 2 protons is $2 \times 1{\cdot}0078 = 2{\cdot}0156$, so that the mass defect of the deuterium is 0·0020, and this is very much smaller than the mass defect of the helium nucleus, which is 0·0292.

Probability of Direct Hits on Nuclei

It may have occurred to the reader by this time that it is a simple matter to release, if not to harness, the energy in the atom. All that we need to do is to bombard the nuclei with protons, α-rays or neutrons, and the release of energy follows automatically. This is true, but the great difficulty is to hit the nucleus.

Suppose we had a pound of dynamite hidden in thousands of bales of wool and we wished to explode it by firing shots from a rifle into the bales. No doubt in time we should get a lucky hit, and if the dynamite exploded in consequence a large amount of energy would be suddenly released. But this method for releasing the energy is wasteful, because we should probably require to fire tens of thousands of bullets before a hit was secured, and in the process we should waste more energy from the explosive propelling the bullets than the dynamite would

give out. It is just the same if we try to release subatomic energy by bombarding the nuclei of atoms with particles.

The chance of a projectile securing a direct hit on the nuclei is so small that when such a hit occurs the liberated energy does not compensate for the expenditure of thousands of projectiles that miss the nuclei. We have already referred to the fact that Blackett secured only eight photographs of head-on collisions of α-particles with the air in a Wilson Cloud Chamber after he had taken 23,000 photographs. It has been pointed out that the diameter of the nucleus of the hydrogen atom or of an electron is about 10^{-5} that of the atom in its normal state. If we could imagine the atom enlarged so that it became a sphere with the diameter of a mile and the nucleus and electron enlarged on the same scale, the diameter of the nucleus and of an electron would be just over half an inch. This will give some conception of the difficulty of obtaining a direct hit on the nucleus.

Rutherford estimated that about one in eight million collisions of the α-particles was effective in transmuting nitrogen into the heavy isotope of oxygen. In addition, when we deal with elements with high atomic numbers, the probability of the projectiles used in the bombardment penetrating the nuclear interior decreases, and this explains why α-particles and protons are more effective in disintegrating the lightest elements. The barriers surrounding the nuclei in the heavier elements present formidable obstacles to the particles even when they strike them, although under certain circumstances this penetration can be made easier if the bombardment is carried out with projectiles of the correct energy, which need not be abnormally high. Even under such conditions the release of energy by bombarding the nucleus of an atom is not a profitable business from the commercial point of view.

Why Ordinary Uranium Does Not Disintegrate Rapidly

Some hope lies in the properties of the neutrons which have such high penetrative power, and reference has already been made to the work of the German physicists and others who bombarded uranium and thorium with these particles. In addition to breaking down into barium and krypton, smaller nuclear portions in the form of a number of neutrons, sometimes as many as three, were ejected, and if these neutrons in turn acted on other intact nuclei a multiplicative process would take place,

the uranium breaking up immediately into the elements referred to and releasing an enormous store of energy. As this did not take place it is interesting to enquire into the reasons.

If you attempt to burn a piece of wood which has been lying in water for some days you will find that it does not readily ignite. If you try to light it by means of a piece of burning paper you will be disappointed. The only way to make it burn is to wait until it dries, or, if you want to burn it at once, to place it on a good fire, which will soon drive off the water absorbed by the pores of the wood, and after this the wood will be consumed. While the wood was wet there was something inhibiting its rapid consumption by the flames, and this inhibition disappeared when it was dried. This crude analogy can be used to explain why uranium does not explode in a fraction of a second when it is bombarded by neutrons, which in their turn release other neutrons to carry on the bombardment.

Possibility of Releasing Enormous Amounts of Energy from Lighter Isotope of Uranium

Ordinary uranium consists of two isotopes, the lighter isotope with atomic weight 235 composing 0·7 per cent of the mixture, and the heavier isotope with atomic weight 238 composing 99·3 per cent of the mixture. The lighter isotope is capable of splitting up into other elements with the emission of neutrons, and if this isotope could be separated from the heavier one a progressive multiplicative process, once started, would continue with terrific rapidity, the lighter isotope exploding with the emission of an enormous amount of energy. The presence of the heavier isotope inhibits this action; it does not split into other elements and emit more neutrons but retains the already emitted neutrons, getting rid of the energy accumulated through the impact of these neutrons by the emission of γ-radiation. For this reason comparatively few of the neutrons produced can take part in the progressive multiplicative process and the uranium mixture remains harmless by the bombardment.

Methods for separating the isotopes have been in operation for some time but the process is extremely slow, and only minute quantities had been isolated until quite recently. In the early part of 1940 it was announced that 10^{-9} gm. had been separated, but the energy resulting from such a small quantity, even if it could be harnessed, would not be of much practical use. A

pound of uranium oxide contains about 95 per cent of pure uranium, and only 0·7 per cent of this, or about 3 gm., is active in neutron multiplication. About ten tons of coal give out as much energy when burned as this small quantity of the lighter isotope, and as it costs considerably more it would be economy to use the energy of uranium if such were possible. But one great difficulty about the use of uranium is its scarcity; while the coal supplies of the world will last for many centuries at the present rate of consumption, the supplies of uranium would probably be exhausted in a century or two. Of course other sources of supply may be found, or, what is equally likely, methods for releasing large quantities of the subatomic energy in other elements may be discovered.

The Running Down of the Universe

We have seen that the proportion of radium to lead in radioactive ores has been used to determine the age of the earth (p. 57), and the question arises why there should be left in the earth any of the uranium, thorium or actinium which head the series given in Table VIII (pp. 58–9). Uranium, thorium and actinium disintegrate and the final product is lead, which, so far as is known, is not radioactive. The first-named elements die, but how did they originate? We know of no other element by the disintegration of whose atoms uranium and its companions are produced, and if the latter have been breaking up into other elements for two or three thousand million years, which can be taken as the age of our planet, why is there anything of them left and from what other source did they arise? This is merely one of many problems still awaiting solution.

The Energy of the Universe Running Down into Heat

There is a law which physicists call the law of increase of entropy, and if we accept it, as practically all physicists do, we must believe that the universe is running down. Some time in the far future—many millions of millions of years hence—the whole energy of the universe will be at a dead level in the form of heat, and nothing, so far as is known, can ever restore it to conditions similar to those prevailing at present. We know that the energy of the universe now is not at a dead level in the form

of heat; it is only necessary to think of the amount of heat that we receive from the sun—not a very important body in comparison with myriads of other stars—to know that the universe is far from being run down. Indeed, we need not even go as far as the sun to learn this fact; we need only think of the amount of energy stored up in the radioactive substances to know that the universe is "wound up", or has been wound up, though at what stage of the running-down process it has arrived it is difficult to say.

There is the possibility that the universe undergoes cycles of winding up and running down, though in what way the former process is accomplished no one knows. If it be true that there are these alternate operations at work we should be obliged to modify the statement that in many millions of millions of years the whole energy of the universe will be at a dead level. Either it will be resuscitated by some unknown means or, long before it would normally reach this condition of death, the winding-up operation would have recommenced.

These speculations have little practical bearing on the immediate problems confronting the human family. One of these is the question of providing sufficient fuel for the industrial requirements of man. In the course of a thousand years or thereabouts our reserves of coal and oil may be at a very low ebb, and unless something can be found to take their place the highly complex industrial system that characterizes civilization will come to an end. It seems practically certain, however, that something will be forthcoming to supply the need, and that this something will be found in the energy latent in the atom.

Cosmic Radiation

The previous discussion on the possibility that the universe is running down leads to a consideration of a phenomenon discovered in comparatively recent times and for which no adequate explanation has yet been offered—cosmic radiation.

We have seen that artificial methods for smashing the nuclei of atoms have been very successful, but nature has provided projectiles which are continually disintegrating the nuclei; these projectiles are in the form of the cosmic radiation which incessantly bombards the surface of the earth. The intensity of this radiation has been found to increase as we ascend in the atmosphere, and this shows that it must come from outside the

earth. One natural assumption is that it emanates from the stars, but this theory is ruled out by the following considerations.

The sun is a star just like the hundreds of stars we see twinkling at night, and though the stars, including the sun, are not exactly similar, some being much larger and also hotter than others, yet on the whole we might say that the sun is a typical star. In these circumstances we should expect, if the cosmic radiation originated in the stars, that the sun, which is incomparably closer to us than any other star, would supply us with the greater portion of the radiation. This is not found to be the case, the radiation not being more intense by day on any part of the earth's surface than it is by night, and hence it is believed that the radiation originates in the distant nebulae.

High Penetrative Power of Cosmic Radiation

Cosmic radiation is the most penetrating form of radiation known up to the present. The most highly penetrating form of radiation that has been considered in the previous chapters is γ-rays, those from radium B being capable of passing through several inches of lead. Cosmic radiation is so penetrating that it can pass through many yards of lead, and on account of this high penetrating power it can travel indefinitely through space because the amount of matter scattered through space is too small to absorb the radiation. It is certain that every second it is breaking up millions of atoms in the bodies of human beings and many other forms of life, and some think that it has a profound physiological effect on living organisms, though the exact nature of these effects is not yet known.

Before cosmic radiation reaches the earth's surface it traverses the atmosphere in which it shatters myriads of molecules, and in addition, before it enters the atmosphere, it encounters the earth's magnetic field. It has been shown how β- and other particles are deflected by a magnetic field, and the same thing applies to the cosmic radiation. It reaches different parts of the earth's surface in different strengths, and from this fact it is inferred that part at least of the radiation consists of electrified particles which have been bent by the earth's magnetic field.

Some kinds of cosmic radiation are more penetrating than others, and there is some support for the view that the most penetrating portions are due to the annihilation of atoms of helium and hydrogen in the simpler atoms, or of electrons and

protons in the more complex atoms. It has been held by some that cosmic radiation is not due to the annihilation of matter but to the building up of matter from radiation—a view which has an important bearing on the theory of the rejuvenescence of the universe. There is still a lot to learn about this form of radiation, which has an interest for others besides the physicist and astronomer. It is practically certain that some day it will be shown to have a decided influence in many biological phenomena.

Reference has been made to the discovery of the positron (p. 40), and it is interesting to know that this took place during investigations on the nâture of cosmic rays. In 1932 C. D. Anderson was using magnetic fields in the laboratory, not to test the nature of the radiation but to test the nature of the *débris* which resulted from the impact of the radiation on atomic nuclei. He found that amongst the ingredients of the *débris* were particles with a positive charge, but the mass of each particle was about equal to that of the electron. If these particles, which were named positrons, emerged from the nuclei, as seemed fairly certain, they must be constituents of the nuclei. The *débris* of nuclei shattered by cosmic radiation is found to contain electrons also, and it has been suggested that the positrons and electrons may be produced in pairs by the bombardment of the nuclei. As soon as they emerge from the nuclei they combine and disappear completely, only the energy of combination remaining to tell that they once existed. The average life of a positron is supposed to be only about 10^{-8} second, and though this brief period is sufficiently long to enable its traces in the Wilson chamber to be photographed, it is not long enough to enable its presence to be shown anywhere else in the universe.

There seems to be a contradiction between the view of the atomic nucleus suggested on p. 37 and the present view that it contains electrons and positrons. Our conception of the nature of the nucleus is, however, by no means final, and in some cases it can be regarded merely as a working hypothesis. Many of the secrets of the nucleus still evade the scrutiny of the physicist.

The New Carnegie Cyclotron

A description of this cyclotron appeared in *Nature*, 154, 393, September 23, 1944, and is reproduced herewith by kind permission of the editors.

"A new giant cyclotron has recently been put into operation at the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. The new cyclotron, one of the two largest in operation in the world (the other being at Berkeley, California), generates particles of 15,000,000 electron volts energy, permitting the most precise measurements ever made of the forces released by atomic disintegration. The cyclotron itself weighs more than 225 tons, has an overall height of 12 feet; it is 30 feet long and 20 feet wide. It took four years to build, at a total cost of 500,000 dollars for the cyclotron, its appurtenances, and the special three-storey building housing the equipment and instrument shop. The magnet is made up of four iron castings, the largest weighing more than fifty tons. Surrounded by this heavy magnet is the accelerating chamber, about 60 inches in diameter, in which atomic particles are produced. The cyclotron is housed ten feet below ground."

Chapter VI

SOLAR AND STELLAR ENERGY

At the present time our attention is directed to the possibilities of the disintegration of the atom for destructive purposes rather than for its commercial applications. So much are we obsessed with the idea that its destructive effects only will be used that we forget what we owe already to the disintegration of the atom in the sun; indeed it would be safe to say that if it were not for such disintegration none of us would be here to speculate on the future applications of the discovery, and life in any form on our planet would be impossible.

Naturally we think that our earth—one of the nine planets revolving round the sun—is the most important body, not only in the solar system, in which it is just a planet on the same footing as the other eight planets, but even in the whole universe. There was a time—not so long ago—when many believed that the whole system of stars throughout the universe was created specially for the benefit of the human race and that man was the very pivot of creation. Around him everything else was centred and for his good everything came into being. Those who held such views received a rude awakening under comparatively recent developments in various branches of science.

Darwinism has shown us that we are evolved from lower forms of life and that biologically man is on the same footing as other species which struggle for existence in the exigencies of a planet where increasing population ever encounters the problem of limited means of sustenance. Developments in astronomy reveal the immensity of the universe in which the earth, and indeed the whole solar system—sun, planets, satellites, etc.—is a mere speck. Geology tells the story of the evolution of our globe through various stages in which, for a long time, it was utterly unfitted as a habitation for life in any form; and palæontology reminds us of the extermination of hundreds of species after the earth was able to sustain life, many beautiful forms disappearing for unknown reasons. In contemplating the destruction of numerous species man is now fully aware of the fact that he may not be exempt from such a fate and that some day in the far future the human family will probably have run its course and, failing to react to inevitable changed conditions, will perish from the face of the earth.

Such thoughts as these should tend to make us less self-centred and to reflect on the utter helplessness of man, in spite of his vaunted knowledge and power, against the forces silently working throughout the universe. Certain changes in some of these forces would annihilate* our planet, together with man and all his works, as well as the other planets associated with our sun. Indeed, it is certain that the annihilation of all life on the earth will take place, though, as will appear later, this will probably not be sudden but will be a gradual process extending over many millions of years. When we enquire what has been responsible for the past vicissitudes of our planet and what will bring about the destruction of so much that we value and cherish, there is the simple answer to the query—the ATOM.

If all the planets except the earth, and also all their satellites, including our earth's satellite—the moon—were blotted out of existence, it would not interfere very seriously with life on the earth. The chief thing we should miss would be the light of the moon and also the tides, which are largely caused by the moon, though the sun would still be able to produce tides, just as he does now, but these are smaller than those for which the moon is responsible. If, however, the sun suddenly ceased to exist, all animal life on the earth would succumb in the course of a few minutes, and vegetable life would quickly succumb as well. There is not the most remote possibility that the sun will

* This would happen if our sun became a Nova (*see* p. 92).

suddenly cease to exist, nor is such necessary to bring about drastic changes on our planet; if we could imagine something inhibiting the sun's output of heat for a very short period, this would cause widespread destruction of life. We can live for a time without the sun's light—though not indefinitely—but his heat is absolutely essential, and without it our planet would become a dead world. No doubt many ancient races who worshipped the sun were aware of the benefits that they derived from his genial rays, but today we take it for granted that he will continue to pour out his light and heat indefinitely—or perhaps we never give the matter a thought.

Past Energy of the Sun Stored Up in our Present-day Fuel

When we burn any form of fuel, wood, coal, oil, etc., we derive a certain amount of heat, and incidentally light as well, but the whole output of energy in the form of heat and light came originally from the sun. This energy was locked up for hundreds of millions of years in the deposits of coal, peat, oil, etc., or other products now utilized by man, and was originally supplied by the sun. The growing leaves and trees and shrubs stored up the energy received from the rays of the sun, and when they died and decomposed and were buried under thousands of feet of subsequent accumulations the energy still remained in them. We dig up the deposits today and the carbon that they contain is ready to unite with the oxygen of the atmosphere in a fire. Chemical action in combustion releases the energy stored up in the far distant ages, and man reaps the advantage hundreds of millions of years later.

Even water and wind power are indirectly due to the heat of the sun. The clouds which give us rain are formed by the evaporation of the waters of the ocean, and this is effected by the heat of the sun. The wind which is utilized to supply power for the windmill is caused by the sun heating different portions of the earth unequally, and as a result there take place the movements in the air that we call the wind. In whatever direction we turn we find the same story—the solar heat is responsible now or has been responsible in the past for the energy that man can utilize on the earth.

How does all this energy of the sun originate? How has the sun been able to send out such vast amounts of energy in the form

of heat and light for at least four or five thousand million years, and probably very much longer, and yet show no signs of ceasing to pour it forth? We can best answer these questions by looking at the amount of energy that the sun emits every minute and then try to find out how long his reserve of energy will last.

The reader knows that heat and energy are convertible and that a certain amount of heat can be turned into energy and vice versa. As a simple example of this truth, hold a brass button in your hand and rub it on a piece of wood for a few seconds. You will find that it is quite hot, the energy expended in rubbing it backwards and forwards appearing as heat. Careful experiments have shown that the expenditure of $4 \cdot 186 \times 10^7$ ergs is just sufficient to raise the temperature of 1 gm. of water through 1° Centigrade. Expressed in the English system, we can say that 776 foot pounds of work, expended in the production of heat, would develop sufficient heat to raise one pound of water through 1° Fahrenheit.

Quantitative Results for the Sun's Output of Energy

Without describing the methods for measuring the energy released by the sun we may say that if we allow the sun's rays to fall for one second perpendicular to a square centimetre on the earth's surface, the energy is equivalent to 1,350,000 ergs. These figures may not convey very much, and we can express them in another way by saying that on each square mile of the earth's surface the sun's energy is equivalent to more than 4½ million horsepower. Although the total amount of energy received each year by the earth from the sun is millions of times the energy annually obtained by the consumption of coal, peat, wood, etc., yet the amount received by our planet is only about four-thousand-millionth of the total amount of energy that the sun is pouring out into space, which is $1 \cdot 2 \times 10^{41}$ ergs per annum.

We can well believe that the surface of the sun must be very hot to radiate so much energy, and it has been found that the temperature of his surface is nearly 6,000° C. If it were not for the protection afforded by our atmosphere this temperature would be sufficient to boil water on the earth's surface, although the mean distance of the earth from the sun is 93 million miles. Of course no body could exist in the solid state at such a temperature as 6,000° C., and so it is that the elements on the sun's

surface are all present in a gaseous form. The temperature of 6,000° C. may seem very high, but it is almost infinitesimal in comparison with the temperature that exists in the interior of the sun, more especially at his centre. Although it is impossible to measure this by direct methods, the physicist is able to deduce the temperature at the centre of the sun and other stars from theoretical considerations. It has been shown in this way that the temperature at the centre of the sun is about 2×10^7, or 20,000,000° Centigrade, and many stars have much higher central temperatures than this, though many have lower temperatures.

What is responsible for such enormous temperatures in the interior of the stars, of which our sun may be taken as typical? When we say that the sun is typical of the other stars it is not implied that all the stars are like the sun in size, mass, temperature, etc. Some stars are nearly a hundred times as massive as the sun, though these are very exceptional, and on the whole the average mass of the stars can be taken as close to that of the sun. Some are millions of times as large as the sun, but these too are exceptional, and in spite of their enormous sizes they are not very much more massive than the sun, being merely huge gas bubbles. Some are much hotter than the sun and some much cooler, but it will be sufficient for the present if we confine our attention to the sun. Later on we shall glance at the conditions in the interiors of a few of the stars.

Theories of the Origin of the Sun's Heat

Suppose the sun were composed of coal which was burning at such a rate that it emitted just as much energy as the sun is doing at present, how long would the sun last under such conditions? It is not difficult to answer this question because the energy developed by burning coal is known, and for the usual type of coal is 3×10^{11} ergs per gram. The sun's mass is 2×10^{33} gm., and hence, if composed of coal, would develop 6×10^{44} ergs by complete combustion. Since the sun's annual radiation is $1{\cdot}2 \times 10^{41}$ ergs, his heat would last only 5,000 years if he were composed of coal. As the sun's output of energy has been going on for at least 4,000 million years it is obvious that ordinary combustion of such substances as are used on the earth is utterly insufficient to account for his heat.

Several theoretical explanations of the sun's heat have been

advanced. Von Helmholtz suggested that the sun contracted from a huge sphere of gas and that this contraction was still going on, a rise of temperature taking place in consequence. A rough illustration can be used from the case of the piston of a pump; the compressed air rises in temperature and it can be made quite warm by continuing to use the pump. If the same thing happened to the sun the increase in temperature at some stage would have stopped the contraction for a time, but when the accumulated heat had been dissipated into space contraction would start again, and the process would be repeated. Unfortunately for the theory, it was shown that the heat developed in this way could not last for more than 20 million years—a mere fraction of the time that the sun has been in existence.

Another theory was that the impact of small bodies like meteors falling on the sun's surface produced sufficient heat by the collision to account for the sun's output of heat. It is quite true that such a bombardment would be responsible for the production of a considerable amount of heat, just as a rifle bullet fired at a target gets warm on impact, and the part of the target struck by the bullet also shows a slight rise in temperature. If this theory were accepted it would be necessary for the sun to double his mass every 30 million years—a view which is utterly untenable.

Within recent times the annihilation of matter has been shown to be a possible explanation of the energy supplied by the sun. We have seen that one gram of matter, if it disappeared in radiation, would be responsible for 9×10^{20} ergs, and as the sun emits $1 \cdot 2 \times 10^{41}$ ergs each year, this would imply the annihilation of $(1 \cdot 2 \times 10^{41})/(9 \times 10^{20}) = 13 \times 10^{19}$ gm. of matter each year, or 41×10^{11} gm. per sec. This is about 4,000,000 tons each second, apparently a very large amount of the sun's mass to be dissipated in radiation, but it is a very minute fraction of the sun's total mass—only about 2×10^{-21}, and hence, assuming that the sun continued to dissipate his mass at the same rate, it would be $1/(2 \times 10^{-21})$ or 5×10^{20} seconds before his whole mass was dissipated in radiation. As 5×10^{20} seconds are $1 \cdot 58 \times 10^{13}$ years, which is about five thousand times as long as our earth has been in existence, we see that the dissipation of the sun's mass is relatively a very slow process. Of course the assumption of equal rates of dissipation during the past, present and future is not valid, but the figures give us some idea of the insignificance of a mere 4 million tons each second when we are dealing with a body as massive as the sun.

For some time it was believed that this was the explanation of the heat radiated by the sun and other stars, but quite recently it has been shown that, while this theory could account for the output of heat, it is unnecessary to postulate the annihilation of matter. Another explanation has been forthcoming, and this will form the subject of the next chapter.

Chapter VII

SUBATOMIC ENERGY IN THE SUN'S INTERIOR

WE can regard the sun and other stars as huge laboratories where nuclear reactions are in progress on a titanic scale, and these reactions require no supervision or experiments to discover the most economical methods for releasing the subatomic energy. If we could produce in our laboratories the enormous temperatures that prevail in the interior of stars and also devise some means for preventing the experimenters and crucibles from evaporating, we would be able to repeat on a very small scale what is taking place throughout the whole universe and what has been in progress for thousands of millions of years. While this is quite impossible, nevertheless the physicist is able to imitate in a small way some of the reactions that are going on in the stars, and it is probable that in the near future he may be in a position to do so on a much larger scale than is possible at present.

If radioactive elements like uranium and thorium existed in large quantities in the sun there would be abundant energy forthcoming from these to account for his enormous outpouring of heat, but the physicist knows that there is not a sufficient quantity of these elements to explain his output of energy. We have seen that a large amount of energy is released when one element is transmuted into another, and the question arises: "Is it possible that this transmutation is in continuous process in the interior of the stars and that this is the explanation of their heat?" We may anticipate what follows by saying that this is exactly what takes place, and the reasons for the transformation will now be dealt with.

Temperature in Interior of the Sun

The interior of the sun, with which we shall deal chiefly, differs mainly from ordinary terrestrial conditions in two respects: (1) The temperature is very much higher than anything to which we have been accustomed on the earth; (2) the pressure is also much greater than those which usually prevail on the earth. The first of these is the more important and requires some consideration.

We know that if we heat a gas—air, for instance—it expands, and we have seen the force of this expansion when overheating a bladder or a child's toy balloon has resulted in a burst. The molecules of the air or any other gas are always in a state of rapid motion in every direction, though the distance through which each molecule moves is very small. This rapid motion of the molecules accounts for the pressure which a gas exercises on a vessel in which it is contained, though ordinarily we are not aware of this pressure because the molecules of air outside the vessel are bombarding its exterior just as the molecules inside, whether of air or any other gas, are bombarding its interior, and a balance prevails. If, however, we pump the air out of the vessel, or force more in, we shall see that the balance is no longer maintained, especially if the vessel is weak and so unable to bear much pressure. In the former case the sides may collapse inwards and in the latter case they may be forced outwards. Instead of pumping a gas into the vessel and so increasing the pressure, we can increase the pressure by heating the gas in the interior, and the higher the temperature to which it is heated the greater will be the pressure. In fact, by increasing the temperature of the gas we make its molecules dash about more rapidly than they would do under a lower temperature, and in consequence the interior pressure is increased.

The same thing happens in the interior of the sun under the very high temperature which prevails there. The particles of gas or matter are dashing about at terrific speeds, and as the pressure is high, and hence the particles are tightly packed, collisions are always taking place on a far greater scale than we experience under terrestrial conditions. We have seen that the high speeds of atomic projectiles like α-particles, protons, neutrons, etc., are responsible for disrupting the nuclei of atoms when direct hits are secured, though the number of direct hits is relatively small. But owing to the tight packing in the sun's

interior the number of direct hits on the nuclei is very much higher than anything that can be obtained in the laboratory for the same volume of gas, and the result is that nuclear transformations go on on an enormous scale.

Another point must be taken into consideration. Owing to the high temperature the electrons will have been driven off from the atoms and the bare nuclei will be left, the electrons rushing about until they are annexed for a brief instant by another nucleus, only to be torn off again by the intense heat. The absence of any form of protection which is afforded by the electrons under laboratory conditions leaves the muclei exposed to more direct hits by the other particles dashing about, and so the bombardment is very much more effective than that which can be carried out in the laboratory.

The Nature of Nuclear Reactions Varies with the Temperature

It must not be concluded that nuclear reactions take place at the same temperature for all the elements. It has already been shown that artificial disintegration of the nuclei becomes more difficult as the atomic weight of the element increases. Up to the present such artificial disintegration has been largely limited to the lighter elements, because those with high atomic weights present a barrier to the entrance of the bombarding particles. The same thing happens in the interior of the stars, the lighter elements being disintegrated at lower temperatures than those that are more massive. Let us look at some of the simplest nuclear reactions which occur when the temperature is about 3 to 7 million degrees Centigrade. It is easier to understand these if they are expressed by the usual symbols, the figure at the top denoting the atomic weight of the element (remembering that for the same element this figure may differ according to its isotope) and the lower figure denoting the atomic number (*see* p. 41).

(1) ${}_3Li^6 + {}_1H^1 \rightarrow {}_2He^4 + {}_2He^3$

(2) ${}_3Li^7 + {}_1H^1 \rightarrow {}_2He^4 + {}_2He^4$

(3) ${}_4Be^9 + {}_1H^1 \rightarrow {}_3Li^6 + {}_2He^4$

(4) ${}_5B^{10} + {}_1H^1 \rightarrow {}_6C^{11}$ + radiation

(5) ${}_5B^{11} + {}_1H^1 \rightarrow {}_2He^4 + {}_2He^4 + {}_2He^4$

In (1) the reaction between hydrogen and the lighter isotope of lithium produces both the isotopes of helium. In (2) the

reaction between hydrogen and the heavier isotope of lithium produces the heavier isotope of helium. In (3) the reaction between hydrogen and the heavier isotope of beryllium produces the lighter isotope of lithium and the heavier isotope of helium. In (4) the reaction between hydrogen and the lighter isotope of boron produces a lighter isotope of carbon, and radiation is emitted. In (5) the reaction between hydrogen and the heavier isotope of boron produces the heavier isotope of helium.

It is possible to reproduce (1) in the laboratory, where a temperature of several thousand degrees is available, but under such conditions the reaction is extremely slow. To effect the complete transformation of lithium into helium by the hydrogen reaction would require many thousands of millions of years under laboratory conditions, though if the temperature could be raised to a million degrees the transformation would be much more rapid. We can scarcely hope for this rapid transformation, however, because, even if a temperature of a million degrees were attainable, long before this took place the laboratory and the experimenters, to say nothing of the surrounding country, would have disappeared in gas.

It has been pointed out that the temperatures at which the above reactions take place lie between 3 and 7 million degrees. It should be added that the reactions are not extremely rapid at such temperatures; that is, they do not occur with explosive violence. If, however, a temperature of 20 million degrees existed, as at the sun's centre, (1) would take place very quickly and the lithium would be used up in a very short time. For this reason it is certain that there cannot be lithium at the centre of the sun and that nuclear reactions other than those shown above must be responsible for the sun's heat. These reactions involve elements much heavier than lithium, though in stars much cooler than the sun the lithium reaction takes place with sufficient slowness to account for their output of heat.

Catalysts

There are several chemical actions which cannot proceed unless a third substance is present—very often in minute quantities. This third substance, which is known as a *catalyst* or *catalytic agent*, remains unchanged during the chemical action. The best instance of a catalyst is found in the case of manganese dioxide, which assists potassium chlorate, when heated, to evolve

oxygen. Potassium chlorate, when heated, evolves oxygen without the presence of manganese dioxide, but a higher temperature is required in this case, and manganese dioxide assists the process without itself undergoing any change. Many other catalysts are used by the chemist, but the above example will suffice to show the properties of such a substance.

There is a series of nuclear reactions in which two elements —carbon and nitrogen—act like a catalyst. It must not be assumed that they function like the catalyst in the ordinary chemical reactions, but the analogy will be helpful, and, like the catalyst in chemical action, they remain unchanged at the end of the series and are ready to take part again in assisting with the nuclear reactions.

Nuclear Transformations in the Sun's Interior

The sequence of nuclear transformations which are believed to take place in the interior of the sun are shown in the following table. The symbols and figures have the usual meaning, and a short explanation of the process follows the table. This nuclear process was proposed independently and almost simultaneously in 1938 by Dr. Hans Bethe, Cornell, U.S.A., and Dr. Carl von Weizäcker, a German physicist.

(1) $C^{12} + H^1 \rightarrow N^{13} + \gamma$-ray
(2) $N^{13} \rightarrow C^{13} + e^+$
(3) $C^{13} + H^1 \rightarrow N^{14} + \gamma$-ray
(4) $N^{14} + H^1 \rightarrow O^{15} + \gamma$-ray
(5) $O^{15} \rightarrow N^{15} + e^+$
(6) $N^{15} + H^1 \rightarrow C^{12} + He^4$
(7) $C^{12} + H^1 \rightarrow N^{13} + \gamma$-ray.

Starting the series with a lighter isotope of carbon, a collision with a proton takes place. As a result of this collision the lighter isotope of nitrogen is formed and some energy in the form of a γ-ray is liberated. In (2) the nucleus of the lighter isotope of nitrogen emits a positron marked e^+, and becomes the nucleus of a heavier carbon isotope. When this carbon isotope is struck by a proton it becomes a heavier isotope of nitrogen, a γ-radiation taking place, as shown in (3). The nucleus of the heavier isotope of nitrogen then collides with a proton, as shown in (4), and the lighter isotope of oxygen is produced, a γ-radiation occurring. This oyygen atom then emits a positron and becomes a heavier

isotope of nitrogen, as seen from (5), and the heavy isotope of nitrogen, struck by a proton, is transformed into a lighter isotope of carbon and helium, see (6).

The series shown in (7) is a repetition of (1), the process being repeated indefinitely, and the nucleus of either carbon or nitrogen appearing in every reaction. They are ready to take part in the reactions every time the series ends with (6), and it will be seen that the real result of the six reactions is that collisions with four protons have ended in the production of a helium nucleus. In other words, owing to the high temperature prevailing near the centre of the sun, hydrogen has been transformed into helium, the catalytic action of carbon and nitrogen assisting in the process.

The result of all this turmoil in the interior of the sun finally makes its way to the surface in the form of radiation of much longer wavelength than that which was emitted in the interior. The longer wavelengths appear in the form of the light and heat which the sun is continually pouring out into space and which are primarily responsible for maintaining life on the earth.

What would happen if the hydrogen content of the sun gave out? Before answering this question it may be said that hydrogen forms about 35 per cent of the sun's mass, and that there is also sufficient quantity of carbon and nitrogen in the sun to ensure catalytic action for a very long period. Thousands of millions of years must elapse before the diminution of the sun's hydrogen content will begin to affect his temperature, and when this does occur it will lead to a *rise* in the temperature. This may seem almost a contradiction to what has been said about the influence of hydrogen in causing the sun's output of energy, but the following considerations will show the reason for the sun's rise of temperature as the hydrogen content diminishes.

The Length of the Sun's Future Life is Enormous

The radiation emitted in the sun's interior by the process just referred to is absorbed by the helium and hydrogen, but much more by the helium than by the hydrogen. Hence the more rapidly the helium is formed the more energy liberated in the reactions is trapped, and so the temperature increases, and this in turn causes more additional nuclear reactions. For this reason the temperature of the sun goes on increasing for a long period, the hydrogen content decreasing at the same time. This

increase of temperature is extremely slow—merely a few degrees in a thousand million years—yet in the course of time it will become appreciable.

In the far-off future the sun's temperature will have become so high that all life on the earth will be gradually exterminated. When the hydrogen content has been all used up or transformed into helium, no more fuel being available to supply the energy, the sun, which had expanded somewhat while the hydrogen was being used, will start to contract, and in doing so will develop enough heat to maintain a high temperature for a time. However, this contraction cannot continue indefinitely, and after many millions of years the sun will have shrunk to such small dimensions that he will emit a mere fraction of the heat he formerly emitted. The end comes when he collapses into a white dwarf—of which many are known in the universe—and the solar system with all its planets and satellites will receive a mere fraction of the heat and light that they derive from the sun at present.

It is certain that the human family will not survive to see the sun pass through his phase of very high temperature before he starts to contract. Even if the high temperature did not render our planet unfit for human habitation it is possible that long before that time man will have run his course, as hundreds of other species have done, and have become extinct. If he did not perish from the earth in the same way as other species, which in some way failed to react to their environments, probably his knowledge of the secrets of nature, in particular of the energy latent in the atom, will have been used in an internecine struggle which will exterminate the human race. Here we enter the realm of speculation, and it is not within the scope of this book to deal with questions relating to the future development in *homo sapiens*. We may add, however, that the poet spoke no dreamer's words but probably a deep scientific truth when he said:

> The weary World is mouldering to decay,
> Its glories wane, its pageants fade away.

Nova or New Star

Reference has been made to a Nova or New Star or Temporary Star, and a brief description of this type of star will now be given.

A Nova rises quite suddenly from being a very obscure or a quite invisible star to one of great brightness in many cases, though in other cases it can be seen only with optical aid. It is famous for a time—but only for a time—because it sinks back again into insignificance in the course of a few months. At the time of writing this, news has been circulated throughout the astronomical world that a Nova has just been discovered on August 28, 1945, in the Constellation of Aquila.*

Many theories have been advanced to explain the cause of a Nova, but none of these has gained general approval, objections being raised to all of them, and at present it is impossible to say what is responsible for a Nova. It is almost certain that it is due to some internal cause which results in a sudden release of energy, but not down deep in the star's interior, because there is good reason to believe that only the superficial layers of the star are affected. Some sudden transformation of the atoms by a process similar to that just described could explain the outburst, but as this does not take place far down in the interior of the star it is difficult to see how a temperature sufficiently high to cause this transformation would be attained. It has been suggested that a Nova is the result of a successful attempt to disintegrate the atom on some other world, but we must not take the joke too seriously.

Whatever be the cause of a Nova, if our sun ever behaved like this type of star (and there is no *a priori* reason why he should not do so) we should know nothing about it, because, owing to the intense heat, the earth and all the other planets of the solar system would be turned into the gaseous condition almost in an instant. Life in every form would be exterminated immediately on the earth and on any other planets where it exists, if it does exist on any of them. From the point of view of the universe of stars, in which our sun with all his attendant planets is but a speck, the consequences of such a catastrophe would be comparable with the effect on the human race of the suicide of a fanatical Japanese soldier. In fact, the net effect of the obliteration of the solar system would be—nothing.

* The page proofs were read in March 1946, and a month previously—Feb. 9th—a Nova of magnitude 3 was discovered in Corona Borealis.

Chapter VIII

COMPARISONS OF EXPLOSIVE FORCES

It lies beyond the scope of this book to deal in detail with explosives, but some information about the relative energy generated by a few well-known explosives and by the disintegration of the atom may prove of interest. It should be mentioned first of all that explosive substances are now of enormous value in the arts of peace, and without their aid many great engineering enterprises would be much more difficult than they are. The fact that man utilizes explosives for the destruction of his fellow man does not imply that their manufacture should be absolutely forbidden. The abuse of a useful commodity is no reason for prohibiting it entirely.

We may define an explosion as the sudden conversion of a solid or liquid body of comparatively small volume into gas or vapour which occupies a volume considerably larger than that of the original substance. In addition, owing to the heat developed, the gas or vapour is expanded with more or less violent force. A substance in such a condition that it is capable of undergoing this change, by the application of heat, by the use of a detonator or by mechanical or any other action, is called an explosive. We have limited the definition to substances in the solid or liquid condition; of course the definition applies also to gases, but owing to the inconvenience of utilizing these, though it is not impossible to do so, it is unnecessary to consider them in dealing with comparative results. Their uses as explosives are largely limited to internal-combustion engines.

The amount of force exerted by an explosive substance depends, in general, upon the volume of gas or vapour produced at the time of the explosion, compared with the volume of the original substance, and also upon the temperature developed. The greater the volume of gas produced and the higher the temperature developed, the greater is the explosive force. There is a great difference between the explosive *force* and the explosive *effect*. Gunpowder explodes slowly in comparison with nitro-glycerin, and though its explosive force is over one-third that of nitro-glycerin, nevertheless the explosive effect of the latter is considerably greater than that of gunpowder, especially if the gunpowder is exploded in an open space. The rapidity of explosion is a very important factor in judging of the probable

effect; the shorter the time required for the complete transformation of the explosive, the greater the effect.

Many explosives burn slowly when lit by a flame in an open space, amongst which are included gunpowder, cordite, guncotton, and also nitro-glycerin, provided it is in small quantities. Other explosives, such as mercury fulminate, lead azide, and other detonators, explode even in the open with great violence, and such explosives which burn very rapidly to detonation in open spaces are known as *detonants*. They are not suitable for propulsion purposes but can be used for military objects and also for mining, as they have a shattering effect.

Some idea of the explosive force of propellents for the modern rifle can be obtained by considering the case of cordite, which has a density of about 1·6, so that 1 cc. of cordite weighs 1·6 gm. If 1 cc. of cordite exploded the gases formed after explosion would occupy a space of about 1,000 cc. if allowed to expand at atmospheric pressure and at normal temperature. This does not take into consideration the high temperature of the gases—probably about 2,000° C. A gas expands by 1/273 of its volume for each increase of 1° C. in its temperature, taking the ordinary temperature of the atmosphere as the starting-point, and hence for a temperature of 2,000° C. its volume would have expanded by 7·3 times its original volume, or for each volume when its temperature was low there would be 8·3 volumes at a temperature of 2,000° C. As the gases after explosion occupy a space of 1,000 cc. at ordinary temperature, the volume at the temperature of 2,000° C. would be 8,300 cc. This is the volume of gas corresponding to an original volume of 1 cc. before the cordite exploded.

The pressure of a gas is measured by the volume which has been compressed into a certain space. Thus, if we pump three volumes of gas into a vessel which previously contained one volume, the internal pressure is four atmospheres, because the vessel contains four volumes of gas where it previously contained only one. In the case of the cordite the pressure, measured in atmospheres, is 8,300. What would be the result of such an enormous pressure on the bullet?

When we speak of a pressure of one atmosphere, assuming normal conditions of barometer and thermometer, it implies that on each sq. in. there is a pressure of about 15 lb., and hence the explosion of 1 cc. of cordite would produce a pressure of $8{,}300 \times 15 = 124{,}500$ lb. per sq. in. The diameter d of the base of a bullet can be taken as 0·30 in. and the area of the base

is 0·071 sq. in. Hence the pressure on this is 124,500 × 0·071 = 8,840 lb., or about 4 tons.

Owing to the difficulty of determining the expansion and temperature very accurately, these figures must not be taken as absolutely correct, but they are sufficiently exact to give an idea of the enormous pressure developed by the explosion of cordite.

Many attempts have been made to arrive at exact determinations of the comparative force of explosives, and these attempts have been based on experiment alone and also on experiment combined with calculations from theoretical considerations. Different experimenters have reached different conclusions—a margin of about 50 per cent discrepancies sometimes being attained in the results. On the assumption of the principle of the mutual convertibility of heat and energy (*see* p. 83) it is possible to calculate the potential energy from the heat of combustion. On this basis, which theoretically is sound, the following table has been compiled, showing the relative and also the absolute amounts of energy developed by the explosion of 1 lb. of different substances.

Explosive Substance	*Potential Energy in Foot Pounds*	*Relative Amount of Energy, Chloride of Nitrogen = 1*
Chloride of nitrogen . .	$48{\cdot}4 \times 10^4$	1
Gunpowder	107	2·21
Picrate of potash	120	2·48
Picrate of potash and saltpetre	138	2·85
Guncotton	160	3·31
Nitro-glycerin	255	5·27

Various methods for comparing the power of explosives by practical means have been used, but the Trauzl Test, or Lead Block Test, is probably the most convenient. In the borehole of a lead block 10 gm. of the explosive are fired and the expansion due to the explosion is measured. This is the principle employed, but various refinements are used, and the mean value of a number of experiments (three at least) is taken. The relative powers of a number of explosives as determined by this method are given in the following table, which has been compiled to compare with the

relative amounts of energy given above, the value for guncotton being taken as the same in each.

Explosive Substance	*Relative Amount of Energy*
Blasting gelatine (8 per cent collodion cotton)	4·10
Guncotton (13 per cent nitrogen)	3·31
Ammonal	3·15
Gelatine dynamite	3·15
Tetryl	2·76
Dynamite No. 1	2·56
Picric acid	2·28
Trinitrotoluene	2·05
Collodion cotton (12 per cent nitrogen)	1·97
Mercury fulminate	1·18
Ammonium nitrate	1·02

The nature of the detonator has an important effect on some explosives. In the Trauzl block test 10 gm. of nitro-glycerin gave an expansion of 190 cc. with a No. 1 detonator, 460 cc. with a No. 6 detonator, and 590 cc. with a No. 8 detonator. Each detonator consists of 80 per cent of mercury fulminate and 20 per cent of potassium chlorate, and the numbers refer to the grams in the charge, these being 0·3, 1·0, and 2·0 respectively. This shows the difficulty in generalizing about the power developed by some explosives unless specific details are given.

Some interesting comparative results are obtained when we consider the amount of potential energy in the same weight of our ordinary fuel—coal for instance. It has been shown that the energy developed by burning coal is 3×10^{11} ergs per gm. Reducing this to foot pounds, we find that a pound of coal contains a little more than 10^7 foot pounds of potential energy, and hence it would be much more economical to use coal as fuel than it would be to use any of the explosives (assuming such were possible) referred to in the table, in which coal would have the relative value 23.

Coal draws its oxygen from the air, and this costs nothing, whereas an explosive must spend a considerable amount of energy in converting its store of oxygen into gas before combination with the carbon can occur (a large number of explosives, but not all, contain carbon). If we could make coal explode like some of the substances given above, instead of utilizing its energy gradually, its value would be greatly enhanced, provided its

potential energy under such conditions remained at the relative value of 23. It is certain, however, that it would not do so.

How do the above figures compare with the energy developed when the atom is disintegrated? It is easy to answer this question, assuming first of all that matter is completely annihilated and transformed into energy, such as was once believed to occur in the sun.

From the formula $E = mc^2$ for the energy released by the disintegration of a mass m gm., c being 3×10^{10} cm./sec., we find that for every gram of matter disintegrated the release of energy is 9×10^{20} ergs, and as 1 lb. is equal to 453·593 gm., the disintegration of 1 lb. of matter would release $4{,}082 \times 10^{20}$ ergs, or 301×10^{14} ft. lb. Comparing this with the values given in the table it will be seen that the explosive energy of matter, assuming its energy could be released suddenly, is $1{\cdot}18 \times 10^{10}$, or more than 10,000 million times that of nitro-glycerin. In other words, the explosive force of 200,000 tons of nitro-glycerin would be similar to that produced by the disintegration of 266 grains of matter.

It has been shown that the lighter isotope of uranium forms about 0·7 per cent of ordinary uranium, and if it be assumed that the lighter isotope alone is responsible for the sudden release of energy (*see* p. 75) it would be necessary to utilize $100/0{\cdot}7 = 143$ times the above amount of matter, that is, $143 \times 266 = 38{,}038$ grains of ordinary uranium to produce the same explosive force as 200,000 tons of nitro-glycerin. Hence if 5½ lb. of ordinary uranium were used, and the energy of its lighter isotope, weighing about 266 grains, were suddenly released, the explosive force would be similar to that produced by the explosion of 200,000 tons of nitro-glycerin, assuming that the mass of the lighter isotope disappears completely in energy. Fortunately for the human race, only about one part in a thousand of the mass is converted into energy, and hence about 266 grains of uranium 235 has an explosive force equivalent to 200 tons of nitro-glycerin.

It is impossible to predict what the explosive *effects* of a large atomic bomb would be. These would depend on many circumstances, such as the local conditions—whether rural or urban, etc. In the former case the high temperature developed would probably destroy all forms of vegetation over a radius of many miles and also all forms of life. In the latter case the heat effects might not be so serious to buildings as it would be to vegetation, but the effects of the blast would cause a terrible

death-roll among the inhabitants. It is also possible that, in addition to instantaneous death among tens of thousands of people in a crowded area, a large number would be incapacitated for the remainder of their lives.

Difficulties will possibly arise if the energy of disintegration of uranium is used for commercial purposes, such as blasting rocks, etc., owing to the fact that such a minute quantity of the lighter isotope would be required. Probably greater difficulties still will arise if attempts are made to harness the energy of matter for driving ships, locomotives, etc. These, however, are matters for the scientific research workers in the future.

Readers who desire further information on the subject can consult a number of elementary treatises on Atomic Physics, among which the following will be found useful:

G. P. Thomson, *The Atom.*
Bertrand Russell, *The ABC of Atoms.*
G. K. T. Conn, *The Nature of the Atom.*
J. A. Crowther, *Ions, Electrons, and Ionizing Radiations.*
C. Moller and Ebbe Rasmussen, *The World and the Atom.*
M. Born, *The Restless Universe.*
L. Infeld, *The World in Modern Science.*
B. C. Sanders, *Order and Chaos in the World of Atoms.*
Arthur K. Solomon, *Why Smash Atoms?*

ADDENDUM

The production of this book was undertaken by request of the publishers a few days after the second atomic bomb had been dropped on Nagasaki, and the MS. was in their hands before certain secrets had been divulged to the general public. For reasons of security it was impossible to deal with the atomic bomb except for a mere passing reference, and the book has been limited mainly to a description of the atom and to a brief reference to the energy latent in the nucleus. After the disclosure of certain matters hitherto kept secret it was decided not to incorporate these in the text but to provide the reader with an outline of the main principles underlying the release of atomic energy. In doing so in the "Addendum" nothing is divulged beyond what has already appeared in publications sanctioned

by the Government. Fuller information by those who wish to know more about the atomic bomb can be obtained from two publications by His Majesty's Stationery Office.* The larger of these, which is a reprint from an American book, is an amazing revelation of the skill and care with which a complex and extensive industrial project was handled and perfected. Although British and American scientists collaborated and ideas and developments were freely discussed, the main expense of the enterprise fell on America.

It is a testimony to the value of free institutions and to the spirit of democracy that a non-military country should have spent thousands of millions of dollars on a scheme which finally matured and which was responsible for the unconditional surrender of a great nation of 70 million people that had threatened to oust the white races from the Pacific. Not the least interesting part of this story is the fact that the project was completed without Congressional sanction and even without its knowledge! "Because of the restrictions of military security there has been no chance for the Congress or the people to debate such questions" (*Atomic Energy*, p. 135).

Chain Reaction

Reference has already been made to the fission of uranium with the production of a number of free neutrons (*see* p. 70). This discovery was of the utmost importance because it was immediately realized that the liberation of more than one neutron, when a uranium nucleus underwent fission, made possible the continuation of the reaction. A rather crude illustration can be used by examining the conditions under which a dump of small-arms ammunition could be suddenly exploded without the application of heat. Instead of one projectile in each cartridge, imagine that there are one, two or three, and that any one of these, striking the percussion cap or detonator, would be capable of exploding the charge in another cartridge, and so on. If the explosive in one cartridge is made to propel its bullets, say two or three, and the cartridges are fairly close together, the whole dump might be easily exploded. If, on the other hand,

* *Statements Relating to the Atomic Bomb.*
Atomic Energy. A General Account of the Development, of Methods of Using Atomic Energy for Military Purposes under the Auspices of the United States Government. By H. D. Smyth.

the cartridges are far apart, or if there is a very small dump, it is quite conceivable that only a few cartridges might be brought into operation. The larger the dump the more chance there is, on the whole, that it will suddenly disappear, because it is more difficult for misses of the projectiles to happen in such circumstances. If half a dozen cartridges are thrown into a small heap and an attempt is made to destroy the heap by exploding one, it is very probable that there will be too many misses to accomplish anything.

This illustration will serve its purpose by showing the difficulty encountered in attempting to disintegrate a small quantity of U-235 by bombarding it with a few neutrons. Some of these might easily pass through the uranium without encountering a nucleus, and even if some did encounter nuclei, and for each encounter the maximum number of three neutrons were released, there is no guarantee that these would be able to produce a chain reaction and so disintegrate the whole mass. They might, and in fact do, pass through a small heap without encountering many nuclei, and in consequence only a minute fraction of the uranium is disintegrated. On the other hand, if the pile were too large, disintegration would take place spontaneously, as there are always a few stray neutrons produced by cosmic rays or by other causes, and experimenters and laboratories would vanish. Expressed in another way, we can describe the escape of neutrons from a quantity of uranium as a surface effect depending on the area of the surface or the square of the diameter of the sphere (if the pile is spherical), and the fission as a volume effect depending on the cube of the diameter, because the fission takes place in every part of the mass. Hence the larger the pile the greater is the volume effect relative to the surface effect.

Critical Size of the Mass

The critical size of a device containing uranium is the size for which the production of free neutrons by fission is just balanced by their loss by escape and also by "non-fission capture"—a term which will be explained later. If the size is smaller than the critical size it will be impossible for a chain reaction to sustain itself, and at one time it was thought that the critical size might be too large for practical purposes. Although the critical size was calculated in 1940 the estimates differed very widely owing to the uncertainty of many factors, on which

more precise information is now available. An important aspect of the problem was the release of energy in a controlled way, which required highly technical skill. The possibility that a chain-reacting system, even under "controlled conditions", might get out of control was not overlooked, and it was considered advisable to conduct certain experiments in an uninhabited locality. The critical size of the active material as used in the atomic bomb is about the same as a large grapefruit, say 4½ inches in diameter. This is, of course, no indication of the size of the bomb itself but solely of the mass of uranium or plutonium which is the explosive ingredient.

Method of Disintegration

One method for producing disintegration of U-235 is to bring together by ordinary mechanical means two or more masses each of which is less than the critical mass, but in such circumstances speed is of the utmost importance. While the parts are being brought together, because of the presence of stray neutrons, the chain reaction may start before the uranium has reached its most compact form. Of course, if disintegration started before this compact form had been attained the bomb could not reach its most compact form afterwards, and the disintegration that occurred might be relatively useless. In addition, the enemy might be presented with valuable material in the form of the uranium which had not disintegrated. It is pointed out in *Atomic Energy* that almost all the technical difficulties of the project come from the extraordinary brevity of this time interval.

A considerable amount of attention was devoted to the problem of assembling critical masses quickly enough without predetonation occurring, and one very obvious method of rapidly assembling an atomic bomb for experimental purposes was to shoot one part as a projectile in a gun against a second part as a target. Even under such circumstances, which seemed to offer a solution of the difficulty, novel problems were introduced by the importance of achieving *sudden and perfect contact* between projectile and target. Questions relating to neutron-absorbers in the bomb, so that it would not detonate prematurely and inefficiently, were also considered in the scheme, but these are largely technical difficulties which lie outside the scope of this book.

Neutrons with Different Speeds

There is a considerable difference between the effects of neutrons which move rapidly and those whose speeds are comparatively slow. The fast neutrons have velocities of the order of thousands of miles a second and the fission of thorium and proto-actinium can be caused only by such fast-moving particles. Neutrons which move comparatively slowly, known as thermal-velocity neutrons, are incapable of causing fission in U-238 but are very effective in the other isotope, U-235. It has been found that these thermal neutrons have a greater probability of causing fission in U-235 than the fast neutrons, and while this fact rendered possible the production of an atomic bomb, it implied the solution of a number of problems involving the conditions under which a chain reaction would occur. These problems exercised the ingenuity of the technologist for a time, and it is certain that under normal conditions of peace very many years would have been required for their solution.

A Chain Reaction Impossible in Ordinary Uranium

Suppose we have a mass of uranium containing the isotopes U-238, U-235, and a minute quantity of U-234 (about 0·006 per cent.), with which we are not now concerned. The isotope U-235 is present to the extent of 0·7 per cent., and hence if neutrons are liberated in a fission process near the centre of the mass there is much greater probability of collisions between these neutrons and U-238 than there is of collisions with U-235. It has been shown that the neutrons have a comparatively long free path because they do not carry a charge of electricity, and hence if the mass of uranium is small most of the neutrons will escape before they can produce fission in U-235. If the mass is large many of the neutrons will have their energies reduced by collisions and will be captured into the "resonance level"* of U-238, and in these circumstances there will be a great loss of neutrons by absorption which does not lead to fission. For this reason a chain reaction will not take place in a mass of uranium unless certain modifications are made. The method for slowing

* When neutron energies are in certain portions of the energy region from 0 to 1,000 electron volts (one electron volt is equal to 1.6×10^{-12} ergs) there is a very strong absorption of the neutrons by U-238. The term "resonance absorption" is used to describe this very strong absorption.

down the fast neutrons and thus introducing the necessary modifications will be dealt with later.

Suppose the fast neutrons were slowed down in some way so that there would be little chance of resonance capture by U-238, it is obvious that these neutrons would have an enhanced chance of producing fission in U-235. It has been shown that these thermal or slow neutrons are more likely to produce fission in U-235 than fast neutrons, and hence by a slowing-down process a chain reaction in a mass of uranium can be made to take place.

Another method for producing a chain reaction is to use concentrated U-235 so that the fast fission neutrons can produce a chain reaction directly. It must be remembered that, though slow neutrons have a greater probability of producing fission in U-235 than have fast neutrons, nevertheless the fast neutrons can and do produce fission in this isotope.

Production of Neptunium and Plutonium

At certain neutron speeds which are intermediate between those required to cause fission of U-238 and the lower speeds which are most effective in producing fission in U-235 a remarkable thing takes place when U-238 is bombarded. Non-fission capture occurs and an element with higher atomic weight than uranium is produced, as the following scheme of the reaction shows:

$$
\begin{aligned}
&{}_{92}U^{238} + {}_{0}n^{1} \longrightarrow {}_{92}U^{239} + \gamma\text{-rays} \\
&{}_{92}U^{239} \longrightarrow {}_{93}Np^{239} + {}_{-1}e^{0} \\
&{}_{93}Np^{239} \longrightarrow {}_{94}Pu^{239} + {}_{-1}e^{0} + \gamma\text{-rays.}
\end{aligned}
$$

In the above scheme ${}_{-1}e^{0}$ denotes an electron, ${}_{0}n^{1}$ denotes a neutron, and Np and Pu are the symbols used for the two new elements named neptunium and plutonium, the former having an atomic number 93 and the latter 94. Each of these new elements, produced artificially by neutron bombardment, has atomic weight 239, so it is no longer true to say that uranium is the heaviest element. (It may be pointed out that the three outer planets of the solar system are Uranus, Neptune and Pluto, and the three elements referred to derive their names from them.)

So far as the release of atomic energy is concerned, neptunium possesses very little interest, but plutonium is fissionable by thermal neutrons and has all the possibilities of a chain reaction

that U-235 possesses. It has the additional advantage that it is more practicable to separate it chemically from U-238 than it is to separate U-235 from U-238. For the release of atomic energy U-235 is of much more importance than U-238, but there are great difficulties in separating the two isotopes because, like other isotopes, they are chemically identical. Chemically identical substances are difficult to separate, and herein is the advantage of plutonium, which, although produced from U-238, *is a different chemical element.*

Various methods were tested for the separation of the two isotopes of uranium, such as by the mass spectrograph, the centrifuge, and gaseous diffusion methods, etc., but it would require too much space to describe these in detail. It will be sufficient to say that it has been possible to isolate U-235 in comparatively large amounts, though the labour and expense involved in the process were enormous. It has been pointed out that thorium and proto-actinium also undergo fission when bombarded by high-speed neutrons, but their use for atomic bombs, especially that of proto-actinium, is restricted. Although thorium is fairly plentiful it has no advantage over uranium, and proto-actinium is too scarce to make its use a practicable proposition.

The production of an atomic bomb involves many technical problems, and even as recently as the spring of 1943 the available information in connection with the design of the atomic bomb was preliminary and inaccurate. Further and extensive work on the critical size, efficiency, method of detonation, etc., was urgently needed. Measurements of the nuclear constants* (a matter of momentous importance) of U-235 and plutonium required improvement, and as only minute quantities of these were then available, nothing more than tentative measurements could be made.

Control of the Chain Reaction

Up to the present nothing has been said about the control of the chain reaction—an absolute necessity if the chief interest is *steady production of power*. It has been shown that thermal neutrons have the highest probability of producing fission in U-235 in a mass of uranium, although the neutrons emitted in the process

* This subject is too involved to discuss in this brief outline. Those who desire full information on the matter should consult the last portion of Chapter XII of *Atomic Energy*.

of fission have high speeds. For this reason it would not be quite correct to say that a chain reaction could maintain itself provided more neutrons were created by fission than were absorbed, because the speed of the neutrons is relevant. The speed at which non-fission capture is most probable is intermediate between the average speed of neutrons emitted in the fission process and the speed at which fission capture is most probable.

Nature of Moderators

One method of slowing down neutrons is to pass them through material of low atomic weight, and hence graphite has been utilized as a moderator for a chain reaction. The neutrons are particles with high speeds, and if they are allowed to collide with particles which are at rest and have comparable masses, the neutrons lose kinetic energy. The more closely the masses are identical the greater the loss of kinetic energy, and hence the lighter elements are the most effective as moderators. If uranium is mixed with a moderator in such a way that when the high-speed fission neutrons are ejected from uranium their speeds are reduced by the moderator so that non-fission capture is probable, a control of the chain reaction is effected.

The Use of Heavy Water

Two important characteristics are essential for a good moderator. (1) It should be of low atomic weight to reduce the kinetic energy of the neutrons. (2) It should have little or no tendency to absorb neutrons. Although lithium and boron possess the first characteristic, and hence from this point of view would make ideal moderators, they are useless because they are able to absorb neutrons. Graphite must be in a very pure state to be effective and for some time it was difficult to obtain it in a very pure condition. Among the elements which are most useful as moderators are hydrogen, deuterium, beryllium, and carbon.

Deuterium, or its compound, heavy water, proved very suitable, but for some time it was not possible to obtain it in sufficient quantity for the large-scale production that was required, though this difficulty was overcome at a later stage. It is remarkable that the Germans, who were far in advance of us in the production of heavy water, did not perfect the atomic

bomb before the Allies. It is possible that if the invasion of the Continent had been delayed for another year the Germans might have been in possession of the weapon which would have ended the war in a few weeks. Our Intelligence Department was fully aware of their activities in securing heavy water in Norway, and their stores and plant received a considerable amount of attention in the winter of 1942-3 from the Royal Air Force and Commandos. These attacks, the last Commando attack in particular, had the effect of reducing very much the output of heavy water in Norway and impeded certain lines of research for which the Allies had much greater freedom.

Protection of the Personnel

Chapter VIII of *Atomic Energy* contains, among various other matters of great interest, an account of the Argonne heavy-water pile and the production of plutonium, which is separated by chemical methods from a quantity of fission products and a larger quantity of uranium. In brief, two types of neutron absorption are required. First of all there is neutron absorption in U-235, which results in fission and maintains the chain reaction as a source of neutrons. Then the neutron absorption in U-238 leads to the formation of plutonium, the desired product. (*See* scheme on p. 104.)

The radiation given off from a pile operating at a high-power level is so strong that the operating personnel dare not approach the pile. In addition, radiation, and especially neutrons, can leak through holes or cracks in the barriers, and for this reason the pile must be enclosed in some absorbing material. These radiation dangers continue through a large part of the separation plant, and remote control is absolutely necessary in handling the uranium after its ejection from the pile. It is a wonderful testimony to the high efficiency of the organization that there were no disasters and that the health of the personnel was unimpaired.

The Slow-neutron Chain

The slow-neutron chain uses ordinary uranium metal and graphite as a moderator. The pile consists of some tens of tons of uranium rods disposed in a "lattice" and spaced at intervals throughout a mass of hundreds of tons of graphite. The fast neutrons escaping from a rod are slowed down by the graphite

and the probability of their encountering the nuclei of U-238 before they are slowed to energies below the resonance level is reduced. When the neutrons diffuse to a uranium rod again they are captured by U-235 and more fissions take place.

If the slow-neutral reaction is to continue it is necessary that the size of the pile should exceed a critical size so that the escape of neutrons from the surface shall not exceed their rate of production. The rate of multiplication of neutrons can be controlled by inserting into the pile rods of material like boron or cadmium, which easily absorb slow neutrons. If these rods are not in use when the reaction begins and the multiplication of neutrons proceeds too rapidly, the rods can be inserted and the rate of multiplication is thus diminished. It is not necessary that the adjustment of the rods should be carried out by the personnel, as there is an automatic arrangement which sets the position of the rods so that the system runs at any desired energy level.

Size of a Pile

A very large pile is necessary to obtain a reacting system, and the first pile was built up on a squash court. The size of the pile can, however, be reduced by using a greater concentration of U-235 or by adding plutonium to the metal, the plutonium acting as a fissile element like U-235. Even with such a reduction the critical size of a slow-neutron system is much larger than that of a fast-neutron reacting system. The critical mass in the latter case is about 20 to 60 lb., but it depends upon a number of factors, such as the shape and the nature of the surroundings, and it is impossible to generalize on the size. While a mass of fissile material which is smaller than the critical mass is stable, if two such masses are brought together so that the total exceeds the critical mass, in a very minute fraction of a second the number of fissions will have multiplied to an enormous extent, assuming that neutrons are active inside the system. A temperature of many millions of degrees is attained and the pressure, which may be tens of millions of atmospheres, will cause widespread devastation. In addition, the radiation from the glowing mass will scorch everything over a large area.

Plutonium and the Atomic Bomb

The advantage of plutonium has been mentioned (*see* p. 105), and as it behaves like U-235 in disintegrating it seems possible

that it will play a very important part in future atomic bombs. It is remarkable that the Americans have not admitted using plutonium on the Japanese cities, but, although several American newspapers have suggested that it was used on Nagasaki, there has been no official confirmation of this, and—of some significance—there has been no official denial.

Uncertainty Regarding the Force of Disintegration

Various estimates are given regarding the force of the explosion from an atomic bomb. Thus, it is believed that one kilogram of U-235 would be equivalent to 2,000 tons of TNT. Two important factors are involved in the calculations. (1) How large a fraction of the available fission energy will be released before the reaction stops. (2) How destructive such a highly concentrated explosion will be. Elsewhere it is stated that the available explosive energy per kg. of uranium is equivalent to 300 tons of TNT, but later the destructiveness of 500,000 tons of TNT is compared to that of 1 to 10 tons of U-235. On p. 135 of *Atomic Energy* a more definite statement is made. There it is asserted that about one-tenth of one per cent. of the mass of U-235 is released in the fission—an estimate which corresponds to that given on p. 98. It is difficult to compare the destructive effects of the ordinary and the atomic bomb because the temperature of several million degrees produced by the explosion of the latter would have far-reaching consequences.

Future of Atomic Energy

It is practically certain that the release of nuclear energy will be applied to industrial purposes within a decade or two, and that there are great future possibilities in its application to medical science. Although developments for these purposes are inevitable it must be admitted that technical developments for military purposes are more likely to take precedence, and atomic bombs of the future will render warfare a very ghastly business. It might be argued that the very ghastliness of atomic bombs will prevent the nations from engaging in war, but this view derives little support from the history of the last thirty or forty years. Fear does not prevent the nations from rushing into war. Europe lived in fear for years before the 1914-18 war and most people realized fully what a great war would imply, but

the nations found themselves drawn into the vortex from which there seemed no way of escape until the Central Powers were vanquished. For many years prior to 1939 it was certain that another European war was coming, and the enormous strides in aviation over a period of 20 years made it inevitable that destruction of life and property on a colossal scale would overtake victors and vanquished alike. Yet this knowledge was utterly ineffective in producing either sanity or any desire in certain quarters to settle disputes by arbitration. Have we any grounds for believing that human nature is more amenable to reason now than it was seven years ago?

The Ethics of Atomic Power

Various sections of the Press have been very free in castigating America for unloosing atomic energy on the Japanese. Some of these criticisms, based ostensibly on moral considerations, were self-contradictory, as they added that the Japanese were almost beaten in any case, and hence the use of the atomic bomb was superfluous. This argument suggests that if the Japanese had not been practically beaten there would have been nothing immoral in the atomic bomb—an argument which reduces moral considerations to a matter of expediency and eliminates any absolute standards. While moral considerations are largely a matter of expediency in which utilitarian principles are very much in evidence, this would scarcely be admitted by those who condemn America.

It is outside the scope of this book to enter into a detailed discussion on the ethics of the matter, but it may be pointed out that the atomic bomb differs from the ordinary bomb merely in degree and not in kind. It is true that the loss of life and the devastation effected by one atomic bomb imply much more hardship and suffering of the civilian population than occurs when a heavy raid is made by bombers, but modern warfare knows no distinction between civilian and combatant. The civilian provides the sinews of war, and no nation will hesitate to destroy the industrial centres which are engaged in the production of military weapons, or the personnel responsible for production. In doing so a nation will utilize the most effective explosive, irrespective of the loss of life of innocent people—the old and infirm and children who are unable to contribute anything to the war effort.

There is very little difference, from the ethical point of view, between wiping out a large part of a Japanese city in a few minutes and wiping out portions of Hamburg or other German cities in a few years. Why should the time factor alter the ethics of the matter, which in either case is a ghastly business?

It is quite possible that the nations will come to some arrangement about the use of the atomic bomb and will agree not to use it except under certain very restricted conditions. It is equally possible that such an agreement will be observed only in so far as it suits the nations engaged in war. A great naval Power could easily lose control of the sea in a few minutes if its capital ships were concentrated in a harbour over which an atomic bomb exploded. A weaker naval Power would not hesitate to wrest the sceptre from its enemy by the use of the atomic bomb, in spite of conventions and agreements.

Release of Atomic Energy May Raise the Standard of Life

One hope remains. It seems highly probable that the release of atomic energy for industrial purposes will raise the standard of living even among backward races and so remove one cause, but by no means all causes, of international rivalry and wars. It is impossible to believe, however, that the raising of the standard of living would be anything more than ephemeral with races—Eastern in particular, like the Japanese and Indians—where the birth-rate is very high and the population is always pressing heavily on the means of sustenance. Even if the release of atomic energy adds considerably to the amenities of life there will still remain many problems inherent in human nature, and these will not find any ready solution in peace conferences or international agreements.

No Golden Age in Front of Us

There have always been some, especially among the poets, who believed that there was a golden age in the past, but this golden age consisted largely of poetic fancies. The golden age, like Ilium of old, has been evoked from the mist and founded on the clouds. The date of its supposed existence has always been many centuries before the days of those who sang its praises. About twenty-seven centuries ago Hesiod declared that it had ended many generations before his time, and he compared the

unfortunate age of violence in which he lived with the peace and justice which had fled the earth. But there is not the slightest trace of a golden age in any ancient records that have come down to us—rather the contrary. We know that among many of the ancient nations the life of the poor was little better than a continuous slavery, and the splendour and luxury in the "golden age" were only for the favoured few.

Some today look forward to a golden age when there will be sufficient to supply the needs of all, when half the population of the world will not suffer from malnutrition, when many of the diseases which now afflict the human family will be eradicated, and when the nations of the world will dwell together in peace. It is a great and noble ideal—still very far from attainment. We are confronted by the stern realities of life and are learning the lesson slowly and painfully that adding to the amenities of life does not solve all our difficulties. We need to learn this lesson more seriously at a time when sentimental indulgence is in danger of banishing wholesome discipline.

Meanwhile, until there are unmistakable signs that human nature has made rapid strides towards higher ideals, an Empire whose life depends upon the control of the sea, and which must still maintain "the far-flung battle line", may find it advantageous to give due consideration to its defences.

APPENDICES

Appendix I

DETERMINATION OF THE VELOCITY OF ELECTRONS

Fig. 14 shows the rays emanating from the cathode and travelling towards the anode. A tunnel is bored through the anode, and by this means the beam from the cathode is narrowed down so that it emerges from the other side of the anode as a fine pencil of rays which strike the vacuum tube at P, where a phosphorescent screen records their impact.

The tube contains two plates, D and E, each of which is connected to the terminals of a battery so as to produce an electrostatic field across the paths of the beam. The negative particles—the electrons—are repelled from the negative plate

and are attracted by the positive plate, and in consequence the spot of phosphorescence which falls at P when the plates are not electrified is displaced to P', and the distance PP' can be measured very accurately by a scale at the end of the tube.

Outside the tube a magnetic field is applied near the anode by an electromagnet, one pole being above and the other below the plane of the diagram. If the electrostatic and magnetic fields are applied simultaneously so that the displacements of the particles in the ray are in opposite directions, it is possible to adjust the intensities of the fields, each of which can be measured, so that equalization takes place, and the spot of light appears in its original position P.

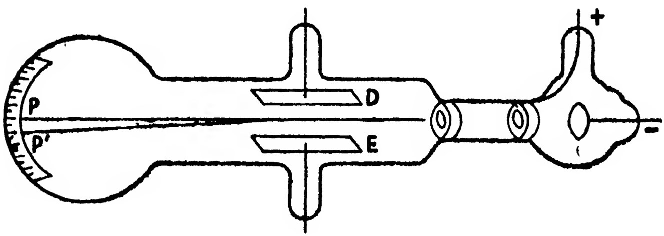

FIG. 14.
Apparatus for finding the velocity of electrons. See text for explanation.

The intensity of the electrostatic field, denoted by F, is not quite the same as a force. The definition of the intensity of an electric field at any point is as follows:

The intensity at any point is the force acting on a small insulated conductor placed at the point and charged with one unit of positive electricity. Hence if e units are placed in the field of intensity F the force acting on the charge is Fe dynes.

In the case of a magnetic field of intensity H the force exerted on a particle carrying a charge e and moving with velocity v is Hev dynes, because the particle moving with this velocity is equivalent to a current ev. When the deflections produced by the two forces are equal and opposite,

$$Fe = Hev, \text{ from which}$$
$$v = F/H.$$

Knowing the values of F and H, the velocity of the particles can be obtained. This velocity for the electrons is found to vary

according to the potential applied to the vacuum tube, but does not depend on the nature of the residual gas in the tube, and is usually about one-tenth the velocity of light.

Appendix II

DETERMINATION OF THE RATIO OF CHARGE TO MASS OF THE ELECTRON

THE apparatus described in Appendix I is used but the plates are not charged, the magnetic field alone being used. By a well-known principle, with which students of electric and magnetic phenomena are conversant, this field acts at right angles to the direction of motion of the electrons, and by a simple dynamical law an electron in such circumstances will describe an orbit which is a circle. As the poles of the electromagnet are supposed to be placed one above and one below the plane of the diagram, the circular orbit will lie in the plane of the diagram; that is, in the plane of the paper.

If r is the radius of the circle described by an electron, it is known from elementary mechanics that the force causing the electron to move in this circle is mv^2/r dynes, where m is the mass of the electron. But as this force is also Hev we have the equation:

$$Hev = mv^2/r, \text{ from which}$$
$$e/m = v/Hr.$$

From the deviations from P and a knowledge of the dimensions of the vacuum tube it is possible to calculate r, and as H is known and v has been already found (see *Appendix I*), e/m is derived.

The best results so far obtained show that e/m is $5{\cdot}27 \times 10^{17}$ e.s.u./gm., e.s.u. denoting electrostatic units.

The definition of an electrostatic unit is derived from the law of inverse squares, as follows:

Suppose we have two small conductors charged with quantities of electricity denoted by q and q' respectively, and their centres are a distance d apart, the force F of attraction or repulsion, depending on whether the charges are of opposite or of the same sign, is given by $F = qq'/d^2$. It is assumed that air is the medium between the charges; if any other medium is used a factor K is introduced into this equation, K varying according

to the medium, but we need not concern ourselves with this for the present purpose. (Notice that F, the force of attraction, is different from *F* the intensity of the electrostatic field, used in *Appendix I.*)

If q and q' are each one unit, then F will be one unit, and as force is measured in dynes and distance in centimetres, the C.G.S. unit of quantity of electricity (electrostatic) is that quantity which exerts a force of one dyne on an equal quantity at a distance of 1 cm., it being assumed that air is the medium.

An example will illustrate the application of the above results.

Two spheres have equal negative charges and their centres are 30 cm. apart. The force of repulsion between them is equal to the weight of 15 mg. Find the charge on each in electrostatic units.

Since 15 mg. = 0·015 gm., which is $0{\cdot}015 \times 981 = 14{\cdot}71$ dynes, 981 being the acceleration due to gravity in cm./sec. per sec., then if q is the quantity of electricity in electrostatic units on each sphere,

$$q^2/30^2 = 14{\cdot}71, \text{ hence}$$
$$q/30 = 3{\cdot}83, \text{ or } q = 115 \text{ approximately.}$$

The value of $e/m = 5{\cdot}27 \times 10^{17}$ e.s.u./gm. should be carefully noted and its meaning properly understood. To explain it a little more fully we shall anticipate some of what follows and say that the mass of an electron is about 9×10^{-28} gm. Hence, because $e/m = 5{\cdot}27 \times 10^{17}$ e.s.u./gm., it follows that

$$e = 5{\cdot}27 \times 10^{17} \times 9 \times 10^{-28} = 4{\cdot}7 \times 10^{-10} \text{ e.s.u.}$$

Now suppose we had two electrons each carrying the above charge, and that they were at a distance 10^{-12} cm. apart—quite a possible distance for electrons—what would be the force of repulsion between them?

$$F = (4{\cdot}7 \times 10^{-10})^2/(10^{-12})^2 = 220{,}900 \text{ dynes.}$$

The repulsive force between two electrons in these circumstances would exceed 220,000 dynes—a relatively great force considering the sizes and masses of the electrons. We can compare it with the gravitational force between the electrons as follows:

Assuming the mass of an electron to be 9×10^{-28} gm., and

the distance between two electrons to be 10^{-12} cm., the force of attraction due to their gravitational pull is

$$(81G \times 10^{-56})/10^{-24} \text{ dyne,}$$

where G is the constant of gravitation, $6 \cdot 67 \times 10^{-8}$ c.g.s. units. Substituting this value of G, the gravitational pull is 54×10^{-39} dyne.

The repulsion between the electrons, due to their electric charges, is, therefore, 4×10^{42} times that due to their gravitational pull.

In order to determine e or m separately it is necessary to know the value of one of them, and then that of the other can be easily determined from the value of e/m, the figures for which have been given. In practice it is easier to measure e and then to derive m from it, and the methods for doing this will be explained in the next Appendix.

Appendix III

CALCULATION OF e/m FOR IONS IN ELECTROLYSIS

THE chemical equivalent of an element is the weight of the element which will replace, or combine with, one part by weight of hydrogen. If the atomic weight of hydrogen is taken as 1 (which is not absolutely correct), the chemical equivalent of an element is its atomic weight divided by its valency. As the atomic weight of hydrogen is 1·008, a better definition of the chemical equivalent is the ratio of its atomic weight to that of hydrogen, divided by its valency. The valency of some elements varies; thus copper in cuprous salts is monovalent and in cupric salts it is divalent. In the former case its chemical equivalent is $63 \cdot 5/1 \cdot 008 = 63$, and in the latter case it is $63 \cdot 5/(1 \cdot 008 \times 2)$, or 31·5. Other elements can be dealt with in a similar manner.

The electro-chemical equivalent (generally expressed as E.C.E.) of an element is the weight in grams which is deposited by the passage of the unit quantity of electricity. The unit quantity in this case is the coulomb, which is 3×10^{9} electrostatic units. If the E.C.E. of one element is accurately determined, the E.C.E. of all the others can be easily found from their

chemical equivalents, and these are known because the atomic weights and valencies are known. It has been found that 1 coulomb deposits 0·001118 gm. of silver, which is monovalent. As the atomic weight of silver is 107·88, and the ratio of this to 1·008 is 107·02, the E.C.E. of hydrogen is 0·001118/107·02 = 0·000010446.

Since 1 coulomb deposits 0·001118 gm. of silver, the quantity required to deposit 107·88 gm. is 107·88/0·001118 = 96,494 coulombs. Also, since it deposits 0·000010446 gm. of hydrogen, the quantity required to deposit 1·008 gm. of hydrogen is 1·008/0·000010446 = 96,494 coulombs. The same value is found for all monovalent elements, as might be expected from the manner of deriving the E.C.E.; in other words, 96,494 coulombs are required to deposit a *gram-atom* of any monovalent element. In the case of divalent, trivalent, etc. atoms, two, three, etc., times the number of coulombs are required to deposit the gram-atom. The *gram-atom* is the quantity of the element equal in grams to the number denoting its atomic weight.

Since 96,494 coulombs deposit 1·008 gm. of hydrogen, and a coulomb is 3×10^{10} e.s.u. units, the quantity required to deposit 1·008 gm. of hydrogen is $3 \times 10^{10} \times 96{,}494 = 2{\cdot}89 \times 10^{14}$ e.s.u. Hence in the case of the hydrogen ions,

$$e/m = 2{\cdot}89 \times 10^{14} \text{ e.s.u./gm.}$$

We have seen that the value of e/m for the electron is

$$e/m = 5{\cdot}27 \times 10^{17} \text{ e.s.u./gm.}$$

The ratio of the latter to e/m for the hydrogen ion is

$$(5{\cdot}27 \times 10^{17})/(2{\cdot}89 \times 10^{14}) = 1{,}824.$$

It is difficult to obtain this result with extreme accuracy but the most recent determinations place its value at 1,844.

Different explanations can be given for the fact that e/m for the electron is more than 1,800 times its value for the hydrogen ion. First of all, it could be explained if we assume that the mass of the electron is the same as that of the hydrogen ion, but its charge is about 1,800 times as great. In the second place, there is no *a priori* reason why the masses of the electron and of the hydrogen ions should not be different, and their charges different as well, but the ratio of charge to mass in one case is

1,800 times what it is in the other. Lastly, the charges can be the same but the hydrogen ion is 1,800 times heavier than the electron. Many considerations show that the third possibility is by far the most likely, and it can be regarded as an established scientific fact that in the electrons we are dealing with particles of extremely small mass—smaller than any entity hitherto discovered.

Appendix IV

DETERMINATION OF THE CHARGE ON THE ELECTRON

Thomson and Townsend were the first to make measurements of the charge on the electron, but more important and more

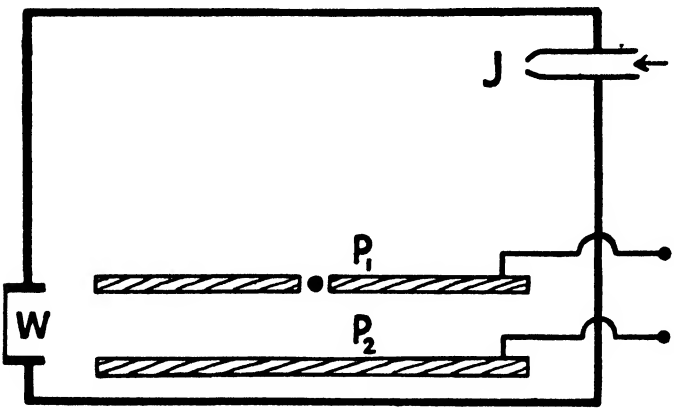

Fig. 15.
Apparatus for determining the charge of the electron. See text for explanation.

accurate work has been carried out by Millikan in comparatively recent times. The apparatus used by him is shown in Fig. 15.

It consists of a tank containing purified air into which a fine spray of oil can be introduced by an atomizer jet *J*. As a result of friction occurring in the process of atomization the fine drops carry small electric charges, and they can be suspended or made to move upwards by means of an electric field. This is supplied

by condenser plates P_1, P_2, connected to a battery which provides a potential difference of about 5,000 volts. A small hole is made in the upper plate, P_1, and in time a drop of oil will enter this and can be kept under observation through a window, its movements being followed by a small telescope with a graduated eyepiece.

Two forces act on the drop. There is the force of gravity tending to make it move downwards, and there is the force of the applied electric field. If the former is the stronger the drop moves downward and if the latter is the stronger it moves upward. Owing to the small diameter of the drop—about 10^{-4} cm.—the resistance of the air to its motion is relatively great and it moves with a constant velocity which is so small that its movements can be easily followed.

The diameter of the drop must be determined with as great an accuracy as possible, because the final results depend on this, and the diameter is found, not directly, owing to the small size of the drop, but indirectly by Stokes's law. This law can be stated as follows:

A small sphere with radius r and density d_d falls through a medium with density d_m and viscosity η; find the value of v, its velocity of fall, if g is the acceleration due to gravity at the place.

Stokes's law asserts that

$$v = 2gr^2(d_d - d_m)/9\eta.$$

Since everything in this equation is known except r, this can be calculated, and knowing the density of the drop from the nature of the oil, its mass m can be found.

The force causing the drop to fall is mg dynes, and if the plates are charged up by connecting them to the battery so that the intensity of the electrostatic field is F, there will be a force of Fe dynes opposing the gravitational force mg, e being the charge on the oil drop. Hence

$$Fe = mg,$$

from which

$$e = mg/F.$$

Various modifications and refinements were introduced into the method, with which we need not deal. One point, however, may be mentioned. Stokes's law has been expressed in a simple formula and it has been assumed that the medium with density d_m is homogeneous. This is not strictly true, because the medium consists of discrete molecules whose free path is not too small

to be ignored in comparison with the size of the drop. In addition it was found necessary to take into consideration the viscosity of the air, but after Millikan had made his first experiments it was shown that the usually accepted value of η was slightly in error. With every refinement that can be introduced the best value obtained shows that the charge e on the electron is $4{\cdot}8 \times 10^{-10}$ e.s.u.

It has been shown that $e/m = 5{\cdot}27 \times 10^{17}$, hence

$$m = (4{\cdot}8 \times 10^{-10})/(5{\cdot}27 \times 10^{17}) = 9{\cdot}11 \times 10^{-28} \text{ gm.}$$

The mass of the proton, which is practically the same as that of the hydrogen atom, because the mass of the electron is only 1/1,844 that of the proton, can be obtained from the above figures by using the results of *Appendix III*. If we take the mass of the proton to be 1844 times that of the electron, the mass of the proton is

$$1844 \times 9{\cdot}11 \times 10^{-28} = 1{\cdot}68 \times 10^{-24} \text{ gm.}$$

When the gas in the discharge tube is helium it has been found that e/m, which, as shown in Appendix II, is $5{\cdot}27 \times 10^{17}$ e.s.u./gm., for hydrogen, is $1{\cdot}446 \times 10^{14}$ e.s.u./gm. Suppose we take the charge as twice that on the electron, that is, assume e to be $9{\cdot}6 \times 10^{-10}$ e.s.u., it follows that

$$9{\cdot}6 \times 10^{-10}/m = 1{\cdot}446 \times 10^{14}, \text{ from which}$$
$$m = (9{\cdot}6 \times 10^{-10})/(1{\cdot}446 \times 10^{14}) = 6{\cdot}64 \times 10^{-24} \text{ gm.}$$

This is the mass of an atom of helium and is approximately four times that of the atom of hydrogen.

Some of the quantitative results given in the Appendices differ slightly from those appearing in the text, but the differences are too small to be of any consequence. Absolutely accurate results are very difficult to obtain when dealing with such small quantities as electrons, protons, etc.

Appendix V

THE MASS OF A MOVING ELECTRON

Einstein's theory shows that a body in motion has a greater mass than the same body at rest. The relation between the two masses can be found as follows:

Let m_0 be the mass of a body at rest and m its mass when it is moving with a velocity v, where v is expressed in terms of the velocity of light.

Then

$$m = m_0/\sqrt{(1 - v^2)}$$

Thus, if an electron has a speed of 10,000 kilometres per second the value of v is $10^4/(3\times10^5) = \frac{1}{3} \times 10^{-1}$. Hence, m denoting the mass of an electron when moving with this speed, and m_0 its mass when its speed is small (there is no such thing as an electron possessing no speed),

$$m = m_0/\sqrt{(1-0\cdot11\times10^{-2})} = m_0(1 + 55 \times 10^{-5}).$$

The increase in mass in the case of the above velocity is therefore less than 6 in 10,000, which is very small, but cases occur where v is as large as 0·99, and the mass of the electron increases considerably in such circumstances.

If $v = 0\cdot99$,

$$m = m_0/\sqrt{(1 - 0\cdot9801)} = m_0/0\cdot141 = 7\cdot1m_0.$$

In this case the mass of the electron is increased sevenfold.

Electrons from radioactive preparations have often very large values of v, and experimental results show that e/m is smaller in these cases than it is in the case of the cathode rays where a is relatively small. It has been found that predictions regarding mass and velocity are verified, and this in itself constitutes one important confirmation of Einstein's special theory of relativity.

Appendix VI

PACKING EFFECT

AFTER starting with the weight of the hydrogen atom as the unit in terms of which all other atomic weights were to be measured, it was disconcerting to discover that atomic weights came out fractional (this is independent of the effect of isotopes). If 1/16 of the weight of oxygen is taken as the unit the atomic weights come out nearly integers except for hydrogen itself, which is 1·008. The conclusion is that the proton in the nucleus of

an atom has less mass than when it exists alone as the nucleus of hydrogen, and this explanation can be accepted on the relativity view.

When the protons (and neutrons) combine to form a complicated nucleus a certain amount of energy is liberated, and, in accordance with the relativity theory which identifies mass and energy, there will be a corresponding loss of mass. The energy liberated by the loss of only a small amount of mass is very great and is expressed by the form mc^2 dynes, where m is the mass that is lost and c is the velocity of light. Thus, if only one milligram of matter is lost, the corresponding amount E of energy released is

$$E = 0{\cdot}001 \times 9 \times 10^{20} = 9 \times 10^{17} \text{ dynes.}$$

Appendix VII

PLANCK'S CONSTANT, PHOTONS AND γ-RAYS

In 1900 a German physicist named Planck suggested that a body can emit or absorb energy in the form of radiation only in definite amounts at a time; in other words, energy behaved like atoms and unit charges of electricity—it appeared in packets, and fractions of packets were excluded. The unit of energy was called the *quantum* and its magnitude depends on the frequency of the radiation. The formula connected energy E, frequency n and Planck's unit h is,

$$E = hn$$

where $h = 6{\cdot}62 \times 10^{-27}$ erg seconds.

It is now believed that radiation travels through space in these small quantities of energy, which in this case are known as *photons*, so that photons are like units or atoms of light. Referring to Table VII on p. 53, suppose we take visible light of wavelength 10^{-5} cm. or frequency 3×10^{15}, then by the above equation

$$E = 6{\cdot}62 \times 10^{-27} \times 3 \times 10^{15} = 19{\cdot}86 \times 10^{-12} \text{ ergs,}$$
or practically 2×10^{-11} ergs.

The equation connecting energy and mass, $E = mc^2$ (*see Appendix VI*) gives $m = E/c^2$, and substituting 2×10^{-11} for E and 3×10^{10} for c,

$$m = (2 \times 10^{-11})/(9 \times 10^{20}) = 2 \times 10^{-32} \text{ gm.}$$

Hence for radiation of this frequency the mass of the photon is 2×10^{-32} gm., which is about 1/4,000 the mass of the electron. In the case of X-rays of frequency 3×10^{19}, the corresponding mass is about one-fourth that of the electron.

If a positron and an electron meet and annihilate each other with the production of radiation in the form of γ-rays, can this be interpreted in the light of the new view of the photon?

The mass of the positron is equal to that of the electron, and the combined mass is, therefore, $2 \times 9{\cdot}1 \times 10^{-28} = 1{\cdot}82 \times 10^{-27}$ gm. If this mass disappears the equivalent in the energy released is

$$E = 1{\cdot}82 \times 10^{-27} \times 9 \times 10^{20} = 1{\cdot}64 \times 10^{-6} \text{ ergs.}$$

Two photons, each with energy $0{\cdot}82 \times 10^{-6}$ ergs, are produced, and applying the equation $E = hn$, or $n = E/h$, we find

$$n = (0{\cdot}82 \times 10^{-6})/(6{\cdot}62 \times 10^{-27}) = 1{\cdot}2 \times 10^{20}.$$

Referring to Table VII, it is seen that the frequency of the radiation emitted when a positron and an electron annihilate each other falls within the region of the γ-rays.

Appendix VIII

THE RITZ COMBINATION PRINCIPLE

Ritz observed that there was a certain frequency in the hydrogen spectral lines which could be represented by simple formulae. He did not offer any explanation for the connection between the observed frequencies and the values deduced from the formulae, and it was left to Bohr to work out the connection.

The frequencies of lines in the radiation emitted by hydrogen can be expressed in the forms

$$R\left(\frac{1}{2^2} - \frac{1}{n^2}\right)$$

$$R\left(\frac{1}{1^2} - \frac{1}{n^2}\right)$$

where R, known as Rydberg's Constant, is $3{\cdot}291 \times 10^{15}$, and n is a whole number with the values 3, 4, 5, etc., in the first expression, and 2, 3, 4, etc., in the second.

As an example of the application of these formulae, let $n = 3$, then the expression inside the brackets in the first of these is $\frac{1}{4} - \frac{1}{9} = \frac{5}{36}$, and in the second $\frac{8}{9}$. The values of these expressions inside the brackets are given below.

n	$\frac{1}{2^2} - \frac{1}{n^2}$	$\frac{1}{1^2} - \frac{1}{n^2}$	$R(\frac{1}{2^2} - \frac{1}{n^2})$	$R(\frac{1}{1^2} - \frac{1}{n^2})$
2		$\frac{3}{4}$		2468×10^{12}
3	$\frac{5}{36}$	$\frac{8}{9}$	457×10^{12}	2925
4	$\frac{3}{16}$	$\frac{15}{16}$	617	3085
5	$\frac{21}{100}$	$\frac{24}{25}$	691	3159

To apply the formulae, take the case of an electron jumping from an orbit of radius 9 to one of radius 4. In the first formula make $n = 3$ and this will satisfy the conditions of a jump from the distance 9 to 4. Then from the figures given above the frequency is 457×10^{12}, and this is the frequency of the radiation emitted by the atom in these circumstances. Other cases can be treated in a similar manner.

Constants Used in the Text

The following constants will be found useful in dealing with some of the quantitative results in the text and also in the *Appendices*.

A centimetre	..	0·3937 inch
A kilometre	..	0·6214 mile
A gram	..	15·43235 grains
A centimetre gram	..	981 ergs
A foot pound	..	$13{\cdot}56 \times 10^6$ ergs
A horsepower	..	$7{\cdot}46 \times 10^9$ ergs per second
An inch	..	2·54 centimetres
A mile	..	1·6093 kilometres
A pound	..	453·593 grams

THE END

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